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Beaked Whale Habitat Characterization and Prediction

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PREFACE

This report was prepared for the Office of Naval Research (ONR) Beaked Whale Habitat Characterization and Prediction Program, Funding Document No. N0001402WX2118; principal investigator is Jessica A. Ward (Code 74); ONR sponsor is Robert Gisiner, Marine Life Science Program Officer (ONR 341).

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13. ABSTRACT (Maximum 200 words)

The objective of this study was to characterize known beaked whale habitat and create a predictive beaked whale habitat model of the Gulf of Mexico and east coast of the United States using available beaked whale sighting data in combination with bathymetry and remotely sensed oceanographic data. To accomplish this objective, three specific tasks were required: establish a sighting and stranding database in a Geographic Information System framework, create a database of oceanographic data on a corresponding spatial and temporal scale, and create/optimize a spatial statistical model for predicting beaked whale presence and absence. Beaked whale habitat optimal classification rates varied from 73.3% to 81.3% for the static models and from 75.5% to 80.3% for the dynamic models of each study area. The classification rate for correctly predicting beaked whale presence ranged from 79.3% to 100.0% for the static models and 85.7% to 94.5% for the dynamic models. Beaked whale habitat prediction has been demonstrated as a promising and effective statistical technique for defining beaked whale habitat in regions where minimal or incomplete survey coverage exists.

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LIST OF ABBREVIATIONS AND ACRONYMS

BSS	Beaufort sea state
CR	Classification rate
CWF	Coast watch format
ENFA	Environmental Niche Factor Analysis
ESRI	Environmental Systems Research Institute
GIS	Geographical Information System
GLM	Generalized Linear Model
GOM	Gulf of Mexico
LDA	Linear Discriminant Analysis
MF	Mid-frequency
ONR	Office of Naval Research
OSR	Observer sighting rate
N/A	Not applicable/not available
NAVOCEANO	Naval Oceanographic Office
NEFSC	Northeast Fisheries Science Center
NEUS	Northeast United States
NLOM	Naval Research Laboratory Layered Ocean Model
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NUWC	Naval Undersea Warfare Center
OSR	Observed sighting rate
SEFSC	Southeast Fisheries Science Center
SEUS	Southeast United States
SPAWAR	Space and Naval Warfare Systems Center
SPUE	Sightings per unit effort
SSH	Sea surface height
SST	Sea surface temperature
U.S.	United States
WGS	World Geodetic System

BEAKED WHALE HABITAT CHARACTERIZATION AND PREDICTION

1. INTRODUCTION

1.1 REQUIREMENT

The phenomenon of mixed species and mass stranding of beaked whales (family *Ziphiidae*) has received widespread attention from the scientific community and the public due to recent high-profile strandings. For example, a U.S. Navy-National Oceanic and Atmospheric Administration (NOAA) investigation into the stranding event that occurred in the Bahamas a few years ago (March 2000) concluded that the presence of MF sonar was "the most plausible source of the acoustic trauma evidenced in the stranded animals" (Department of Commerce, 2001). The report detailed several research needs, including the need for a better understanding of beaked whale distribution and habitat preferences through predictive modeling techniques. Little direct evidence of the distribution of most beaked whale species is currently available. Characterization of beaked whale distributions and habitat use through modeling will help to fill in some of the data gaps and lead to a better understanding of where beaked whale presence might occur. To address the need, the Office of Naval Research (ONR) sponsored this program to characterize and predict beaked whale habitats by:

1. Research and collection of global beaked whale sighting and stranding data,
2. Development of a centralized database of beaked whale sighting and stranding data,
3. Incorporation of the database into a Geographic Information System (GIS),
4. Characterization of the relationship between beaked whale presence and oceanographic variables potentially representative of their habitat, and
5. Development of a statistical beaked whale habitat prediction model to provide Navy environmental planners with maps of beaked whale known and predicted habitat.

The research and collection of beaked whale sighting data were primarily performed as a separate effort by project collaborators Colin MacLeod (University of Aberdeen) and Angela D'Amico (Space and Naval Warfare Systems Center (SPAWAR)). Therefore, the methods used to locate and collate these data are not presented in this report. Data were obtained by the Naval Undersea Warfare Center Division (NUWC), Newport, RI, from the Northeast and Southeast Fisheries Science Centers (NEFSC and SEFSC, respectively) as well as from several other sources in western North Atlantic. The primary focus of this report is to address requirements 2 through 5 (above), progressing from the development of the centralized database to the resulting product, i.e., predictions of beaked whale distribution.

1.2 BEAKED WHALE ECOLOGY

Beaked whales (family *Ziphiidae*) are the least known of all cetacean families but are second only to dolphins (family *Delphinidae*) in diversity with 21 described species worldwide. Most species are known from only a small number of stranded specimens and several have never been observed alive (Dalebout et al., 2002). The lack of knowledge stems from their oceanic distribution and elusive behaviors that make observation difficult. For example, most beaked whales tend to dive when disturbed (Mead, 1989; Ritter and Brederlau, 1999; Hooker and Whitehead, 2002) and remain submerged for such long periods of time that there is a high probability that they will never surface within the visual range of observers aboard a moving survey vessel (Barlow et al., 1997). Additionally, surface behaviors are often quiescent and unremarkable without conspicuous blows (Hooker et al., 1999). Although beaked whales are infrequently observed, they are found in all the world's oceans.

Most *Ziphiidae* species inhabit very deep waters. Even in places where they are known to be present, little data are available upon which to base an understanding about their distributions. For example, the distribution of most *Mesoplodon* (14 species) is almost entirely deduced from records of stranded animals and their stomach contents (Mead, 1989). Even the most cosmopolitan of beaked whales, Cuvier's beaked whale (*Ziphius cavirostris*), which has been observed in all oceans except Arctic and Antarctic waters and has more recorded sightings than any other beaked whale, has little information available on distribution, biology, and ecology excepting that derived primarily from strandings (Santos et al., 2001). Data collected during a targeted fishery for Cuvier's beaked whale indicated that they were primarily found in waters deeper than 1000 m where the most abundant consumed prey were deep-water fish (Nishiwaki and Oguro, 1972).

Only one population of beaked whale has been extensively studied with published findings, the northern bottlenose whale (*Hyperoodon ampullatus*) in the Gully off Nova Scotia. Their primary activity in the Gully is foraging, mainly for adult squid of the genus *Gonatus* (Hooker and Baird, 1999a; Hooker et al., 2001). Mature *Gonatus* live near the sea-floor at depths of approximately 1000 m (Kristensen, 1984; Moiseev, 1991). Observation of foraging activities led the researchers to believe that the northern bottlenose whale forages in deeper portions of the water column than any other mammal (Hooker and Baird, 1999b). Hooker and Whitehead (2002) also observed variations in bottlenose whale distribution related to shifts in the Gulf Stream and suggested that natural variation in hydrodynamic processes may have affected beaked whale prey availability. However, the understanding gained about fine-scale habitat use in the Gully only provided clues to the wider distribution of bottlenose whales in the North Atlantic.

Currently, most clues to distribution patterns of various beaked whale species are related to identification of prey, as was the case with the northern bottlenose whale. The limited published information on beaked whale diet indicates that they feed primarily on oceanic mesopelagic and benthic cephalopods, mostly squid, although the remains of oceanic fish and crustaceans have been found among the stomach contents (Nishiwaki and Oguro, 1972; Heyning, 1989; Mead, 1989; Debrot and Barros, 1994; Santos et al., 2001). The prey items identified for a specific species varied by individual and geographic location, most likely reflecting differences in prey

availability (Clarke, 1996). Many cephalopods congregate to spawn, presenting a concentrated resource for predators such as beaked whales (Clarke, 1996; Hanlon and Messenger, 1996). Additionally, many cephalopods are less difficult to catch than other prey due to their quick exhaustion after fast swimming, making them more vulnerable to the method by which beaked whales feed, i.e., suction (Heyning, 1996). Many species consumed by beaked whales that live at great depths are luminescent and are particularly gelatinous, presenting poor sonar targets (Clarke, 1996), which contributes to the difficulty in detection by passive acoustic methods during study.

1.3 CONCEPTUAL HABITAT MODEL

Four basic steps are involved in creating a species habitat model: conceptual development, statistical formulation, model evaluation, and optimization. The first step to creating a statistical model of beaked whale habitat is the development of a conceptual model of their ecology. The objective of this conceptual model is to create a list of quantifiable ecological parameters that are believed to be the causal, driving forces for beaked whale distribution and abundance (Guisan and Zimmerman, 2000).

One of the more important activities for the survival of any species is foraging. Therefore, environmental variables that affect foraging success are likely to be good candidates for an effective habitat model. Beaked whales are known to occur along regions with steep bathymetric relief. Indirect variables affecting beaked whale ecology are likely to include all environmental factors related to prey concentration. Recent studies on the influence of the environment on cephalopods have noted a correlation between water depth, proximity to thermal fronts, and bottom temperature as potential indicators of *Loligo sp.* abundance (Brunetti et al., 1998; Waluda and Pierce, 1998). Topographic variables representing the movement of water masses, such as depth, slope, and aspect, are also important. For example, areas with a high variance of aspect and steep slope are likely to represent canyon features with which beaked whales have often been associated.

Several recent studies that compared beaked whale presence/absence to environmental variables in the Gulf of Mexico (GOM) and in the U.S. Atlantic also provided insight in the development of parameters for this study. In the GOM, beaked whales were associated with areas of steep sea surface temperature (SST) gradient and the deepest bottom depth within the survey area (Davis et al.,1998). Another study found that beaked whale distributions were associated with areas of higher relative salinity, depths over the upper to lower slope, and sea surface height (SSH) anomaly confluence zones or at the periphery of a confluence zone (Davis et al., 2002). Hamazaki (2002) found that beaked whales on the U.S. east coast occurred in water with the steepest slopes, i.e., in waters with surface temperatures of 21-26°C and depths greater than 1500 m.

The environmental parameters selected for this study include bottom depth, slope, aspect, SST, proximity to thermal fronts, and SSH anomaly.

1.4 STATISTICAL MODEL

Available studies have used multiple methods to characterize and predict cetacean habitat. Most of these methods have relied on a presence/absence approach using survey data with effort. These methods include chi-squared goodness-of-fit (Woodley and Gaskin, 1996; Moore, 2000), Kruskall-Wallis one-way analysis of variance (Davis et al., 1998; Baumgartner et al., 2001), Kolmogorv-Smirnov goodness-of-fit (Hooker et al., 1999), habitat selection ratios (Moore, 2000), linear regression (Watts and Gaskin, 1985; Hooker et al., 1999), logistic regression (Davis et al., 2002; Hamazaki, 2002), multivariate analysis of variance (Baumgartner et al., 2001), and Linear Discriminant Analysis (LDA) (Baumgartner et al., 2001). Another method available that requires only presence data is Environmental Niche Factor Analysis (ENFA) (Hirzel et al., 2002). Logistic regression, LDA, and ENFA were used in this study.

1.5 STUDY AREAS

Three study areas were chosen based upon the availability of survey data with effort: the GOM, southeast United States (SEUS), and northeast United States (NEUS) (figure 1). Multiple naval operating areas are collocated within the study areas, ensuring that the results of this study may be applicable for environmental planning purposes.

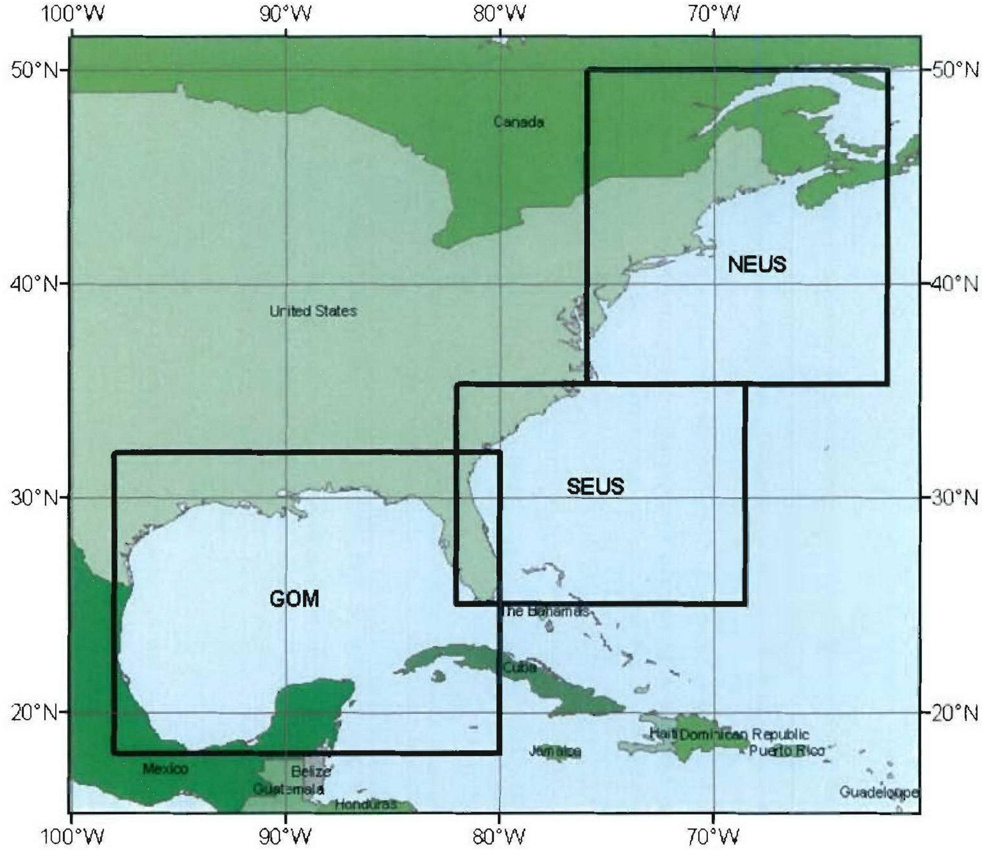


Figure 1. Beaked Whale Habitat Characterization and Prediction Study Areas

2. METHODOLOGY

2.1 GEOGRAPHIC INFORMATION SYSTEM DATABASE

Data Acquisition

The NUWC Division Newport and collaborators from SPAWAR and the University of Aberdeen were responsible for collecting sightings, strandings, and associated available effort data from around the world. Specifically, NUWC Division Newport was responsible for collecting data from the NEFSC and SEFSC offices. SPAWAR was responsible for collecting data from the Northwest and Southwest Fisheries Science Centers and the Mediterranean Sea. The University of Aberdeen was tasked with collecting data from international organizations and literature. Additionally, the collaborators coordinated to identify and acquire all available beaked whale data, including data published and available through the literature

Data Compilation

Records Without Effort Data. Once collected by the individual collaborators, records were sent to NUWC Division Newport for compilation and quality control. A total of 5,197 sighting and stranding records were collected from a wide range of sources, including published literature, individual researchers, local stranding networks, and national and international agencies. These data were incorporated into a master Microsoft Access database that included the species identification, type of record, number of animals, number of adult males, number of adult females, number of male juveniles/calves, number of female juveniles/calves, number of unidentified juveniles/calves, and body length. Additional parameters entered, when available, included the data type, ocean area, SST (Celsius), depth (meters), and any additional comments. The ocean area defined the ocean (North Atlantic, Southern, etc.) and was assigned by the data locator. The Southern Ocean was defined as the region south of 55°S.

To more easily facilitate quality control and record identification, a number of additional fields were entered. These included the data locator, data source, original record number, (new) record number, and identification (ID). The original record number is the number assigned by the originator of the data if it was part of a larger database (for example, the number of the record in the Smithsonian stranding database). The record number is the number assigned by the locator. The ID is a sequential number assigned as the record was entered into the compiled database.

The type of record identifies how the record was collected. This includes visual, visual (opportunistic), visual (aerial), visual (shipboard), visual (shore based), observer program, single stranding, mass stranding, acoustic (passive detection), bycatch, satellite tracked, and unknown. To further qualitatively identify the validity of the data, a field was added for sighting category. This field identified whether the data were collected opportunistically, systematically, or by another method (e.g., whaling records, whale watch vessel, targeted study, or unknown method).

Effort Data. Sightings data with associated effort data (all events) included date, time, latitude, longitude, Beaufort Sea State (BSS), visibility, altitude, species identification, and number of animals. In the aerial SEFSC data, the sea state was not entered as a BSS and needed conversion. The conversion was performed using the description of the SEFSC sea state and defining the equivalent in BSS (table 1).

In the SEFSC data, the visibility was a subjective evaluation supplied by the observer and ranged from 1 (great) to 5 (poor).

Once entered into an Access database, a "Make Table" query was designed to sort the records chronologically. A unique sequential event number was added to each record to facilitate record identification. These records were then exported as a comma-delimited text file and imported into MATLAB for quality control.

Table 1. Conversion of SEFSC Sea State to Beaufort Sea State (BSS)

SEFSC Sea State	Description	BSS
0	Slick calm, mirror like	0
1	Small waves, few whitecaps	1.5
2	Whitecaps 0-33%, Waves 1-2 feet	3
3	Whitecaps 33-50%, Waves 2-3 feet	3.5
4	Whitecaps 50-65%, Waves 2-3 feet	5
5	Whitecaps >65% Waves > 5 feet	6

Quality Control of Records Without Effort Data. Once incorporated into the database, the records were sorted and duplicate records were identified and removed. The data were then plotted in an ESRI GIS project. Records that plotted on land or had otherwise impossible coordinates (e.g., a latitude of 126° N) were identified. These records were referred back to the data locator for verification. If the issue could not be resolved, the record was removed and maintained in a list of questionable records. If the ocean area did not match the coordinates given, the record was again referred back to the data locator for clarification. Other parameters that were reviewed included date and data type to make sure they were consistent with other fields in the record.

Quality Control of Effort Data. The effort data were incorporated into MATLAB files and the legs of each survey transect were plotted sequentially by event number. These plots were evaluated visually for errors and obvious outliers were removed.

2.2 OCEANOGRAPHIC DATA

Bathymetry

The General Bathymetric Chart of the Oceans (GEBCO) Digital Atlas (GEBCO, 2003) 1-minute arc degree database was used for this study. Bathymetry for each study area was remapped in ArcGIS to a regionally specific equirectangular projection using the WGS 1984 coordinate system (table 2). The standard parallel and central meridian were chosen to be the approximate center of each study area to minimize distortion. Slope and aspect maps were also created within ArcGIS. Maps were exported from ArcGIS in an ASCII format for use in MATLAB.

Table 2. Study Area Map Projections

Study Area	Lower Lat. (°)	Upper Lat. (°)	West Long. (°)	East Long. (°)	Central Meridian (°)	Standard Parallel (°)
GOM	18.00	32.00	–98.00	–80.00	–89.00	24.50
SEUS	25.00	35.25	–82.00	–68.50	–75.00	30.00
NEUS	35.25	50.00	–76.00	–60.00*	–63.00*	42.50

*Central meridian based on original study area boundary at –50° degrees longitude. The area boundary was modified upon subsequent receipt of survey data.

Sea Surface Temperature Data

Remotely sensed SST data were obtained from the NOAA Satellite Active Archive Coast Watch database (http://www.saa.noaa.gov/nsaa/products/welcome). Full regional (~1.1 km/pixel resolution) daytime split-window non-linear SST images and their corresponding cloud masks were downloaded for each study area. The SST images were then cloud-masked using the Coast Watch Format (CWF) Software and Utilities 2.0 function "cwfcmask." A master projection file for each study area was created using the CWF 3.2 function "cwmaster." The master projection was then applied to each cloud-masked SST image using the function "cwregister" that outputs all files in hierarchical data format. These images were individually geo-registered to the coastline within MATLAB.

Frontal edge detection was implemented in MATLAB following the methodology of Cayula and Cornillon (1992, 1995). Each image is median filtered using a 3 x 3 pixel window. A 32 x 32 pixel sliding window is then stepped over the entire window using 50% overlap. At each step several criteria are evaluated to determine if a frontal edge is present within the window (figure 2). First, a histogram of the temperatures is evaluated to determine if a bimodal distribution is present, indicating the presence of a temperature front. If the distribution is bimodal, the threshold value best separating the two populations is identified. Next, the cohesion

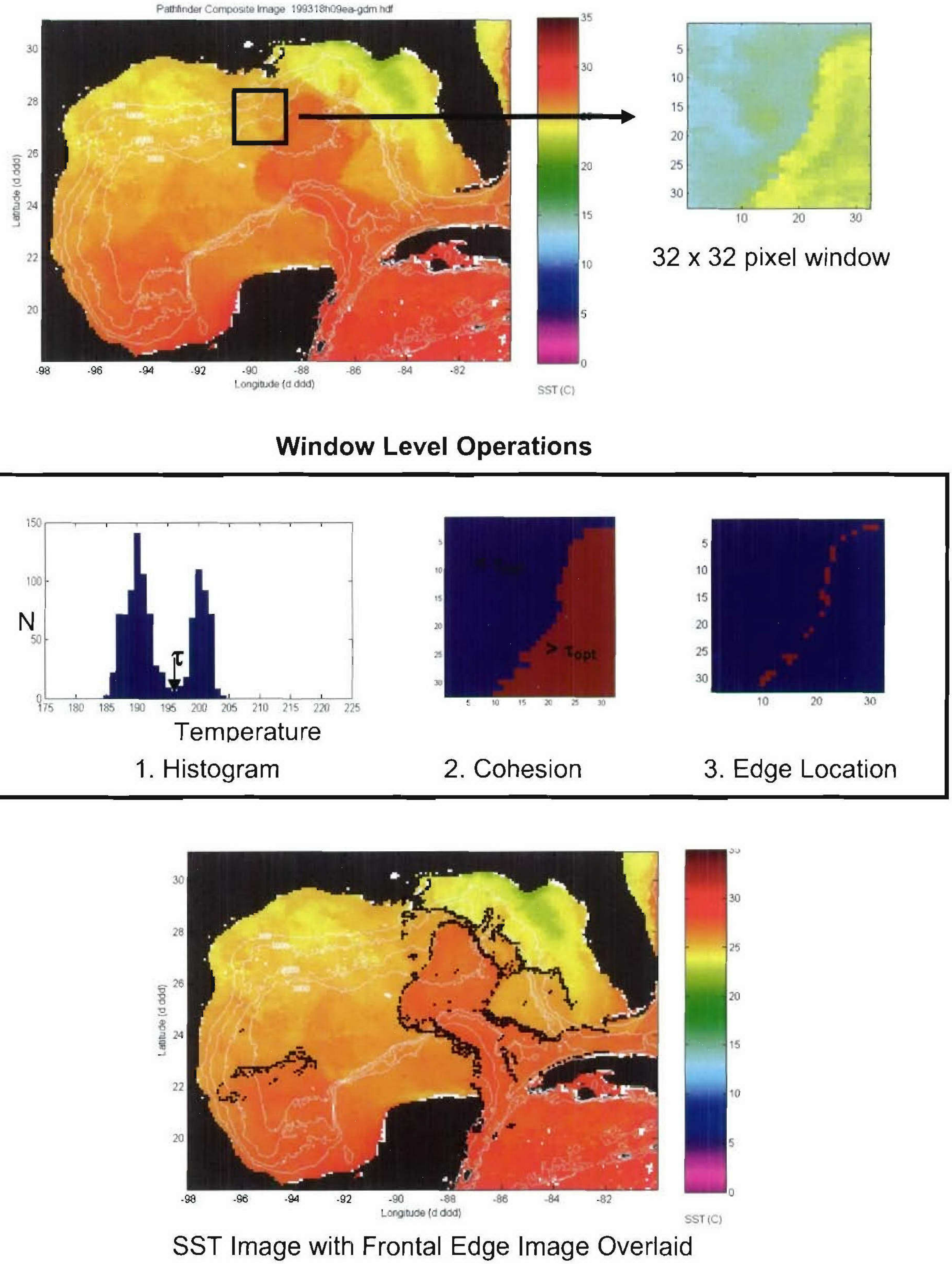


Figure 2. Example of the Frontal Edge Detection Process

of each population of temperature values is evaluated to determine whether the two populations each form a distinct area within the window. Once this condition is met, a final algorithm identifies the location of the frontal edge pixels within the window. The pixels identified at each window are stored at the image level and then used to form a composite frontal edge image with the same dimensions as the original SST image. Available images corresponding to the weeks of each year were used to create a mean SST image and composite edge image for use in this study.

Sea Surface Height

The SSH anomaly data were obtained from the Naval Research Laboratory (NRL) Layered Ocean Model (NLOM). NLOM is an operational production run daily by the Naval Oceanographic Office (NAVOCEANO) at 1/16° global resolution (Rhodes et al., 2003). The NLOM uses atmospheric forcing from the Navy Operational Global Atmospheric Prediction Systems and assimilation of SST and satellite altimeter data from the NAVOCEANO Altimeter Data Fusion Center. Archived daily global SSH anomaly results from 1993 through 2000 were provided by NRL.for use in this project. These results are bounded by the 200-m isobath; no model results are available within the shallower Continental Shelf region. The daily images were averaged into a mean 7-day image corresponding to the weeks of each year for use in the dynamic modeling portion of this study.

2.3 HABITAT MODELING

The beaked whale sightings data from the GIS database were used to evaluate several habitat characterization and prediction methodologies. For sighting data with effort, both static (time-invariant) and dynamic (time-variant) presence-absence models were evaluated. In the absence of sufficient effort data, all sightings data (with and without effort) were combined to develop a presence-only model. All statistical analysis was conducted within MATLAB version 6.5.0 using the Statistics Toolbox version 4.1, in addition to user specific m-files developed for this program.

Prior to each data set being input into a multivariate model, several pre-processing steps were taken. The multivariate models discussed below assume multivariate normality, which was assessed by evaluating whether each variable was univariate normal. Univariate normality was tested using the Lilliefors hypothesis test of composite normality and the Jarque-Bera hypothesis test of composite normality (The Mathworks, Inc., 2002). These tests are of limited use as univariate normality does not necessarily ensure multivariate normality (McGarigal et al, 2000). The data were optionally normalized using the Box-Cox transform (Legendre and Legendre, 1998). For each variable, values for beaked whale presence and absence cells were compared using the Kolmogorov-Smirnov goodness-of-fit hypothesis test to determine if they share the same continuous distribution (The Mathworks, Inc., 2002). The correlation matrix of the standardized data set was calculated and assessed for collinearity prior to input into the multivariate model. The output of this preprocessing is a standardized and optionally normalized data set for input into a multivariate model. For each data set, the mean, median, minimum, maximum, and standard deviation of all cells with beaked whales sightings present were tabulated.

Three multivariate models were chosen for use in this study: Linear Discriminant Analysis (LDA), Generalized Linear Model (GLM), and Environmental Niche Factor Analysis (ENFA). LDA and GLM, implemented as logistic regression, were chosen because of their relatively simple implementation, wide acceptance in the scientific community, and proven ability for use in habitat prediction models (Legendre and Legendre, 1998; McGarigal et al., 2000; Guisan and Zimmerman, 2000). These models require presence-absence data as the dependent variable. No prior probabilities of group membership were assumed. The output of LDA is also presence-absence (0 or 1) in contrast to GLM, which predicts probability of presence (0 to 1). Although relatively new to the field of habitat prediction, ENFA was also chosen since the method requires only presence data for the dependent variable. Since much of the data collected for beaked whale sightings does not have associated effort, ENFA allows a larger sample size to be used than either LDA or GLM. ENFA routines were developed in MATLAB following the methodology presented in Hirzel et al. (2001) and Hirzel and Guisan (2002). The MATLAB script file results were validated using ENFA version 2.0 prior to use for this project (Hirzel et al., 2004).

Static Model Analysis

The objective of the static model was to develop the simplest possible prediction model using minimal, time-invariant input with presence-absence data available for validation. The static model was limited to four environmental variables: depth (meters), slope (degrees), aspect (degrees), and standard deviation of aspect (degrees). The optimal variable subset was determined for each of three spatial resolutions (5, 9, and 15 minutes) using two statistical methods, LDA and GLM. In addition, the models were compared using untransformed and Box-Cox transformed data. Thus, 288 model simulations were completed for each study area.

Each of the 288 model simulations was evaluated using a jackknife method. This method involves cycling through each of N observations using $N - 1$ observations to train the classifier and make a prediction for the N^{th} observation. This provides an estimate of the classification effectiveness of each subset of variables. The resulting classification effectiveness for each simulation was evaluated using a classification matrix (table 3). For each multivariate method, an optimal subset of variables was chosen based on the mean correct classification rate (CR) for cells correctly predicted as present and cells correctly predicted as absent. The multivariate model with the best overall mean correct classification rate was then chosen as the optimal static model for each study area.

Table 3. Example Classification Matrix for LDA and GLM

Actual Membership	Predicted Membership		Total in Each Group	Correct CR
	Presence	Absence		
Presence	n_{11}	n_{12}	n_1 (n_{11}+n_{12})	n_{11}/n_1
Absence	n_{21}	n_{22}	n_2 (n_{21}+n_{22})	n_{22}/n_2
Total Predicted in Each Group	n_{p1} (n_{11}+n_{21})	n_{p2} (n_{12}+n_{22})		

Dynamic Model Analysis

The objective of the dynamic model was to develop a more comprehensive habitat characterization and prediction model to evaluate in more detail the relationship of environment to preferred beaked whale habitat. This model used 12 environmental variables: mean depth, maximum difference in depth, mean slope, standard deviation of slope, mean aspect, standard deviation of aspect, distance to nearest frontal edge, mean frontal frequency, mean SST, standard deviation of SST, mean SSH, and standard deviation of SSH. Data were extracted to form a 15-minute spatial resolution grid and evaluated using two multivariate models, LDA and GLM.

Due to the large number of model simulations required to complete an all-subsets analysis (i.e., 16,340 simulations for each study area), the computationally time consuming jackknife method was not used for each simulation. Instead, the classification matrix was calculated using the same data for training and classification. The optimal environmental variable subset selected for each multivariate method was then evaluated using the jackknife method to provide a final estimate of classification effectiveness. In addition, the familiar forward step-wise logistic regression method was compared to the results obtained using an all-subsets methodology. In every case, the environmental variable subset selected by the all-variables method was either the same or performed better than that selected by the forward step-wise method. Since the computation time was not significantly different, the all-subsets method was used for this study. The multivariate model with the best overall mean correct CR was then chosen as the optimal dynamic model for each study area.

Presence-Only Model

In addition to static model analysis and dynamic model analysis, a third model based only on beaked whale presence data, i.e., ENFA methodology, was used. This model was used mainly when the presence/absence data were insufficient to develop a GLM or LDA model. The ENFA model used all sighting data, including those without associated effort, to develop habitat prediction maps.

3. RESULTS

3.1 GLOBAL BEAKED WHALE SIGHTING AND STRANDING DATABASE

The global beaked whale database contains 5,197 records, which include 2,617 sighting events (figure 3); 2,047 stranding events (figure 4); 276 bycatch events (figure 5); and 257 events of unknown classification (figure 6). An event represents a record, such as a sighting, at a specific position and time. Each event may include one or more beaked whales. It is important to note that areas with no data do not necessarily indicate areas of beaked whale absence. In many areas, such as along the U.S. west coast, beaked whales are known to be present from literature; however, survey and sighting data were unattainable from the collection source. While most of the data consists of sightings without effort and strandings, significant aerial and shipboard survey data were provided by the SEFSC and NEFSC for the GOM and U.S. east coast; hence, the focus is on these areas.

For each of the study areas, table 4 describes the quantity of sighting data with and without effort available for analysis, and table 5 summarizes the number of sighting events available with respect to year and corresponding oceanographic data availability.

Table 4. Number of Beaked Whales Sighted With and Without Effort Data for the Three Study Areas

Study Area	Sightings With Effort	Sightings Without Effort
GOM	172	281
SEUS	38	167
NEUS	275	4873

Table 5. Beaked Whale Effort and Corresponding Oceanographic Data Availability

Data Source	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	Total # Sighting Events	Total # Beaked Whales Sighted
GOM Effort	9	13	18		10	6	1	4	12	12		85	172
SEUS Effort	3			0	0	0	9	0				14	38
NEUS Effort				36		2	53				11	102	275
CoastWatch SST													
NLOM SSH													

Note: Numbers in effort cells indicate the number of sighting events for each year; highlighted areas indicate that data source is available.

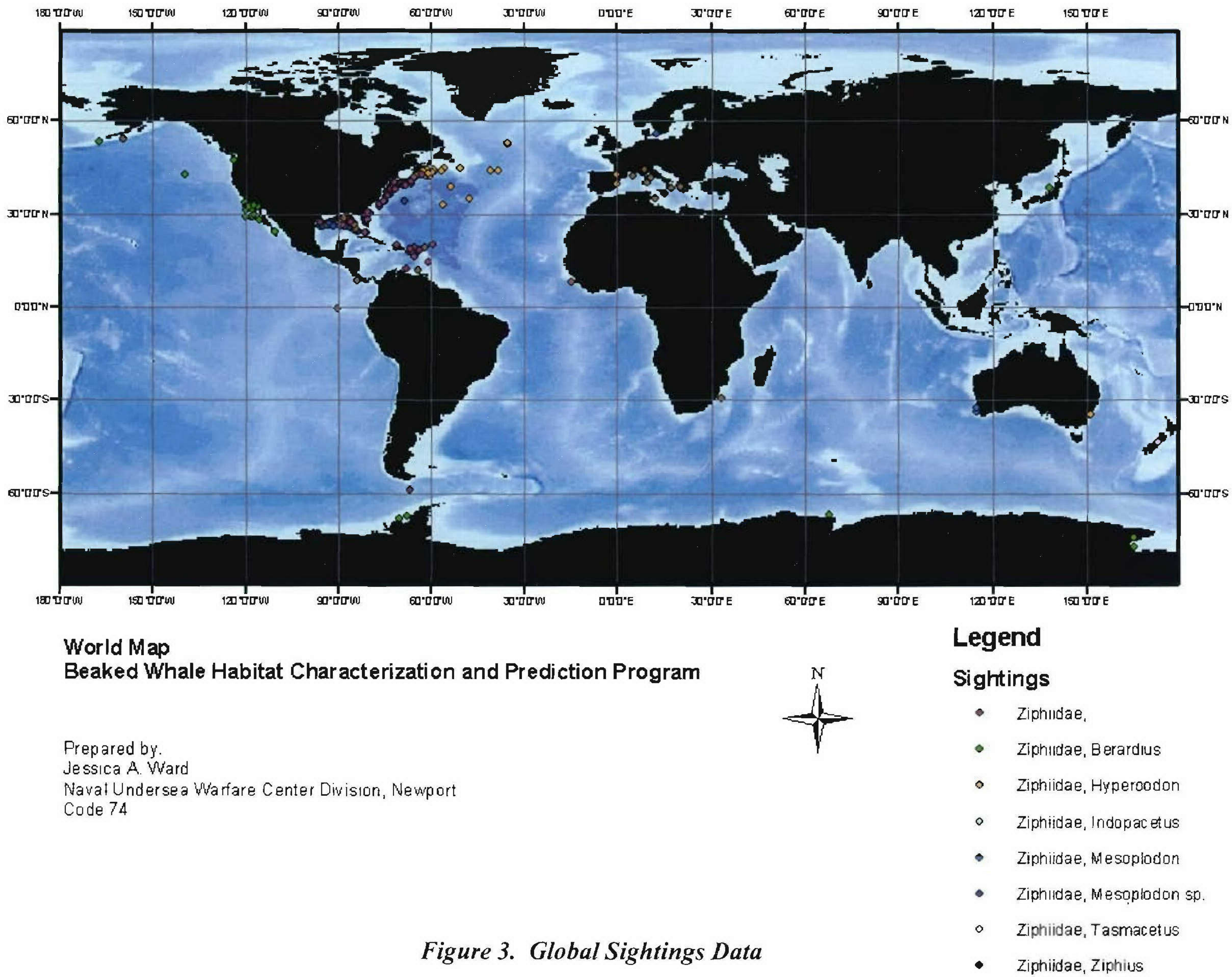


Figure 3. Global Sightings Data

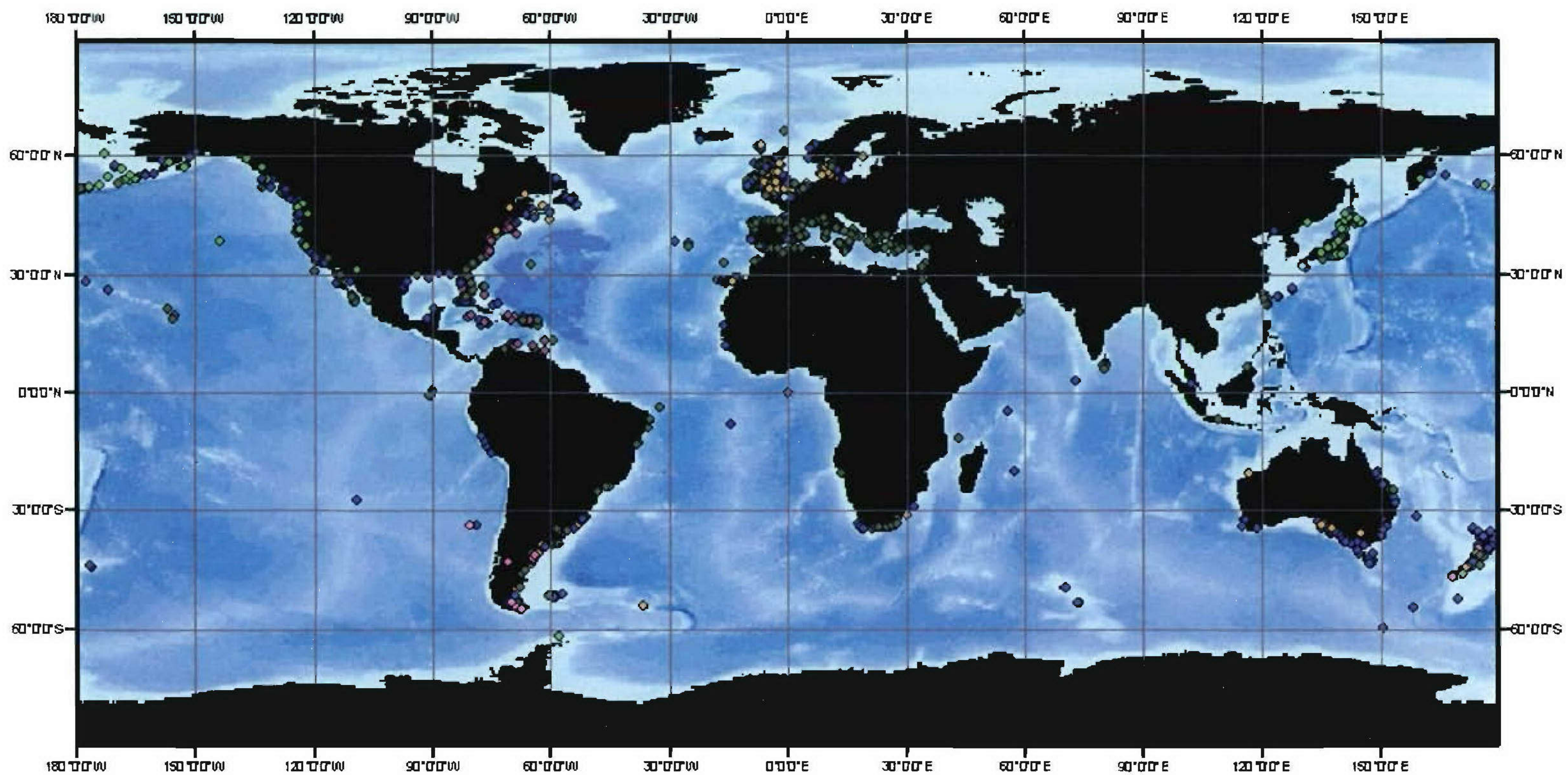


Figure 4. Global Strandings Data

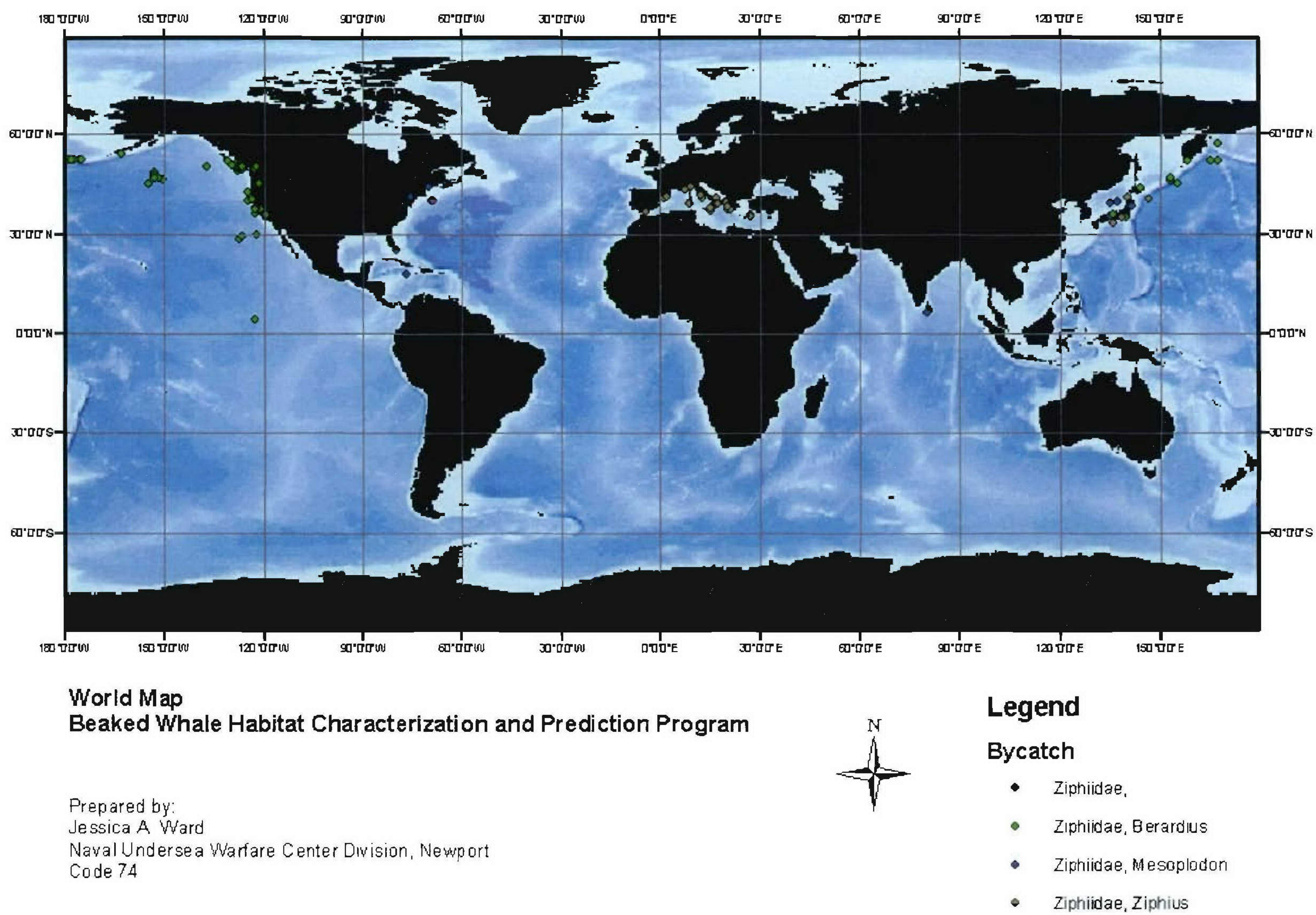


Figure 5. Global Bycatch Data

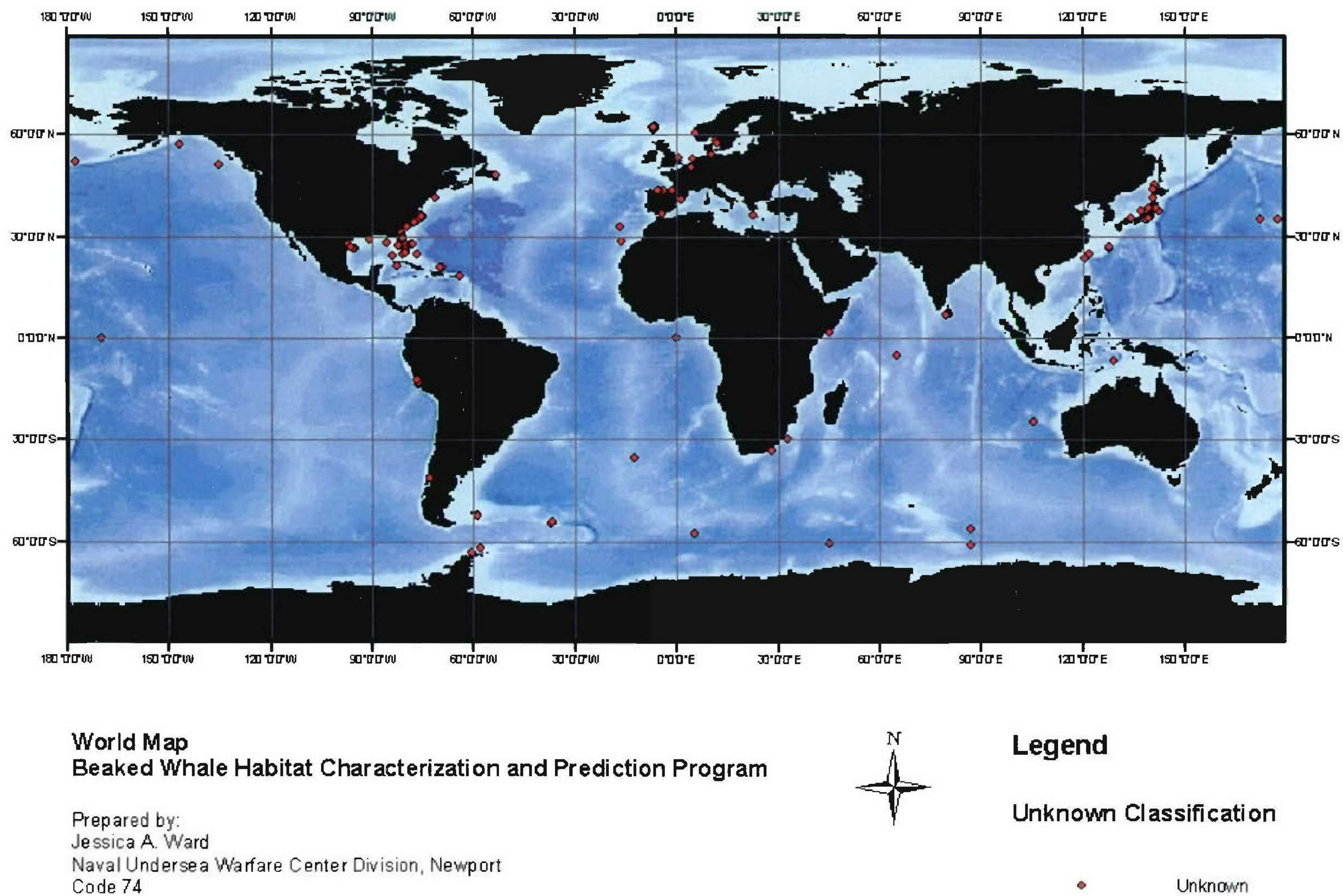


Figure 6. Beaked Whales of Unknown Sighting/Stranding/Bycatch Classification

3.2 GULF OF MEXICO STUDY AREA

Beaked whale data available for the GOM study area included the following events (number of individuals indicated in parentheses): 4 (4) mass strandings, 20 (20) single strandings, 6 (6) unclassified strandings, 9 (16) unknown, 24 (60) visual aerial sightings, and 108 (221) visual shipboard sightings. Species identification for the sighting data was typically limited to genus, but in those cases where a more detailed identification was made, the data also included *Mesoplodon sp.*, *Mesoplodon densirostris*, *Mesoplodon europaeus*, and *Ziphius cavirostris* (figure 7). Stranding data included the additional species *Mesoplodon gervasi* and *Mesoplodon bidens*.

Static Analysis

The mean depth, slope, aspect, and standard deviation of the aspect for each cell were used to characterize and predict habitat at cell resolutions of 5, 10, and 15 minutes (figures 7 through 9).

Habitat Characterization. Table 6 summarizes the values of 5-minute cells in which beaked whales were present. Even when transformed, none of the variables passed either the Lilliefors or Jarque-Bera test for goodness-of-fit to a normal distribution ($P < 0.05$). While the untransformed variables were uncorrelated, mean depth and mean slope were correlated ($r > 0.5$) for all transformed variable models. For all models, the mean depth, mean slope, and standard deviation of aspect of cells with beaked whales present differed significantly from those cells with beaked whales absent (Kolmogorov-Smirnov test, $P < 0.05$).

Table 6. Habitat Characteristics of 5-Minute Cells with Beaked Whales Present in the GOM (N = 76)

Variable	Minimum	Maximum	Mean	Standard Deviation
Mean depth (m)	419.61	3486.48	1778.10	796.97
Mean slope (°)	0.01	12.97	2.08	2.22
Mean aspect (°)	73.49	281.41	182.25	55.83
Std dev of aspect (°)	1.47	129.97	34.40	31.96

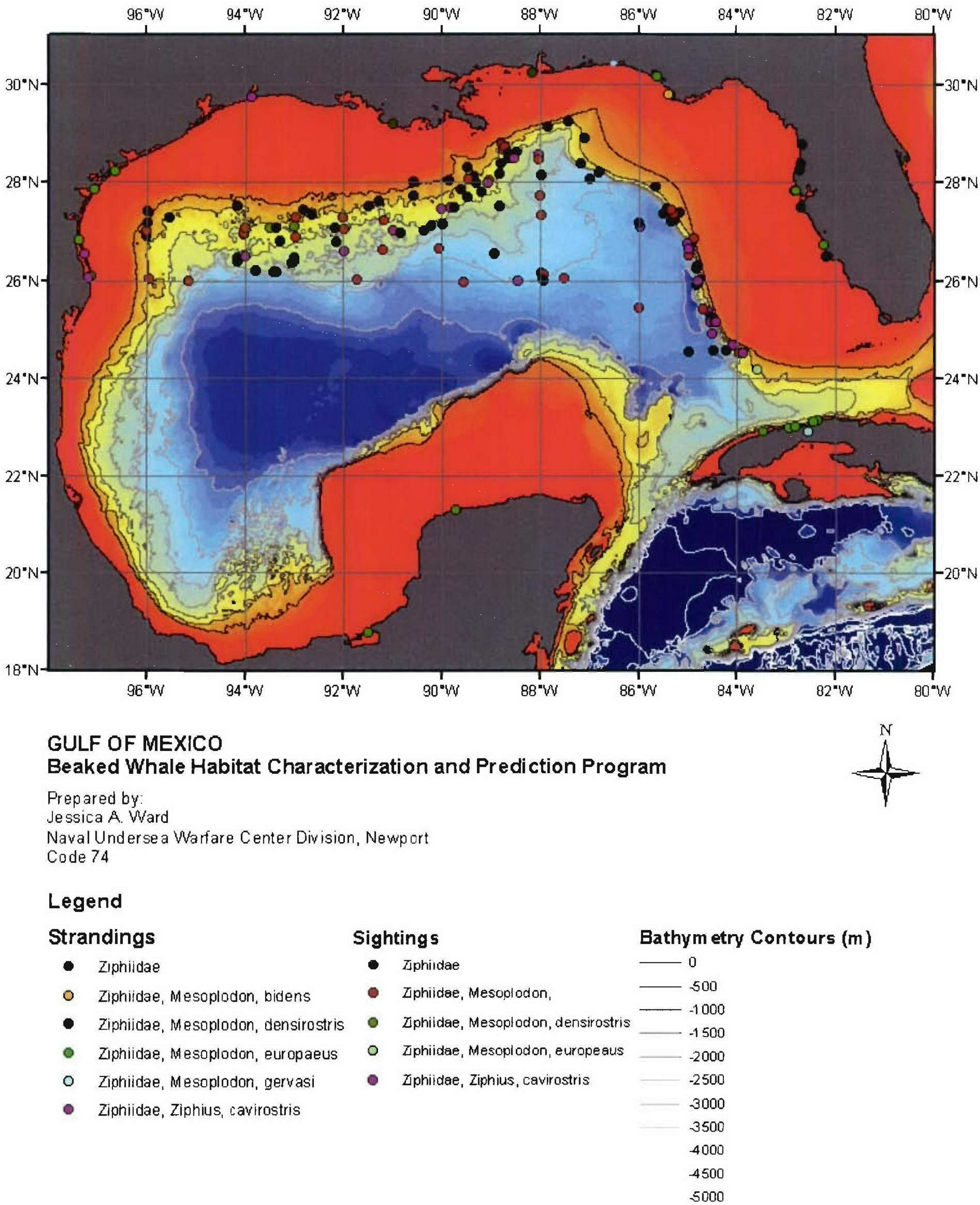


Figure 7. GOM Sightings and Strandings Overlaid on Depth Data

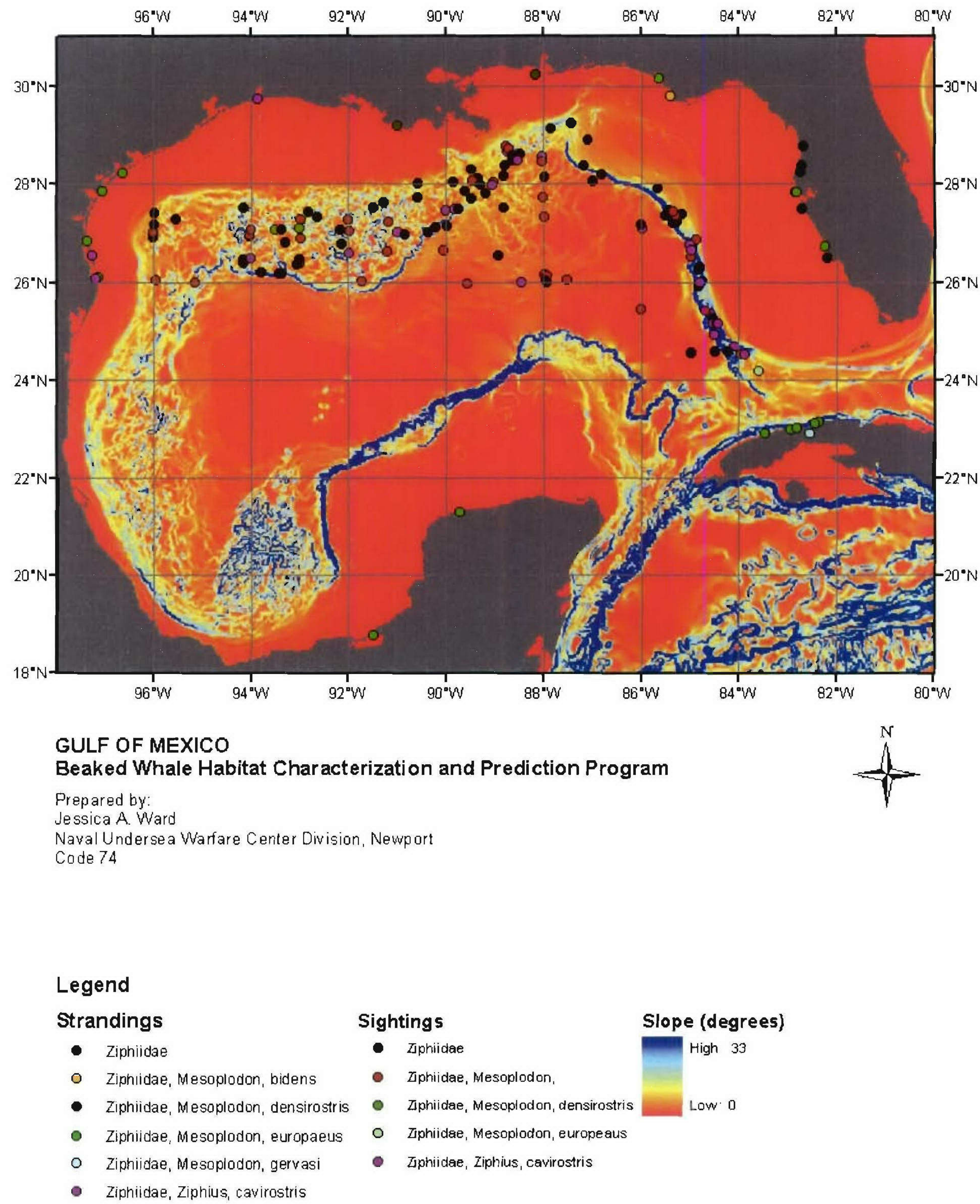


Figure 8. GOM Sightings and Strandings Overlaid on Slope Data

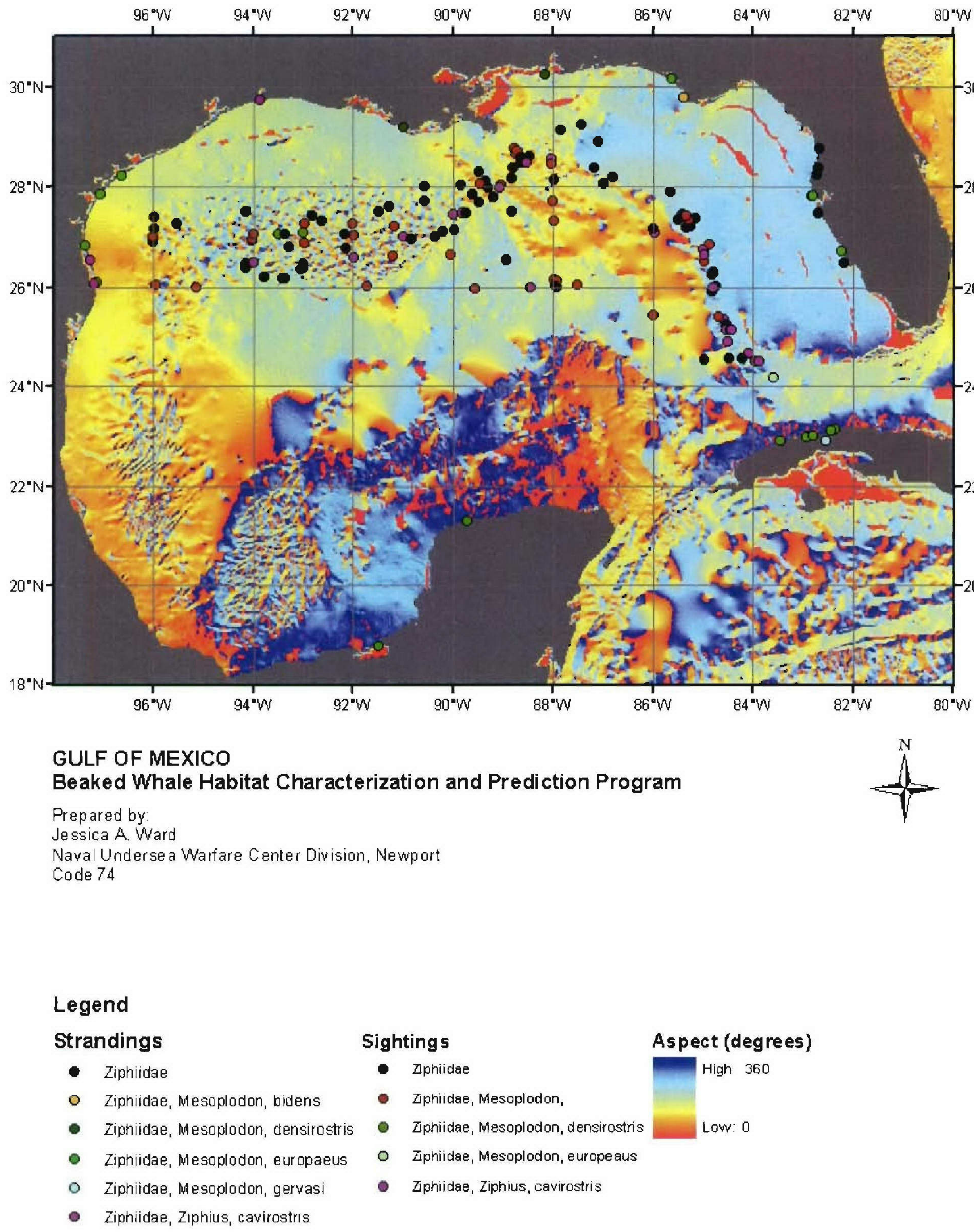


Figure 9. GOM Sightings and Strandings Overlaid on Aspect Data

Classification Effectiveness. The optimal model for each cell resolution based on the mean correct CR is presented in table 7. In all cases, models based on the transformed data performed better than untransformed data. The mean correct CR did not vary significantly between cell size; therefore, the 15-minute cell resolution was used for the dynamic analysis to minimize computation time.

Table 7. GOM Static Model Classification Effectiveness Results

Cell Size (min)	Box-Cox Trans.	Model	Variables	$N_{present}$	% Present Correct	N_{absent}	% Absent Correct	Mean % Correct
5	Yes	LDA	Depth, Aspect	76	93.42	4735	60.49	76.95
9	Yes	LDA	Depth, Aspect, Aspect std. dev.	69	94.2	1727	59.24	76.72
15	Yes	GLM	Depth	64	92.19	766	61.23	76.71

Habitat Prediction. The optimal classification models identified in table 7 were applied to the entire GOM study area to produce a broader geographic estimation of habitat (figure 10). For illustrative purposes, the habitat predicted at 5-minute resolution using the optimal GLM based only on depth is also presented in figures 11 through 14. The 15-minute static model results are included for comparison to the 15-minute dynamic model results (figures 15 through 18). The beaked whale presence-absence data used to develop the models are overlaid on the predicted habitat data in figures 12 and 16.

All three results indicate that areas with a depth greater than 1000 m were generally predicted to be potential beaked whale habitat. The 5-minute LDA results, which included the aspect variable, differed slightly, which indicated potential habitat in shallower canyon areas in the northeastern GOM and habitat not occurring until the deeper waters of the southwestern GOM. The increased likelihood of presence with depth in the GLM is due to the linear nature of the model based only a single variable. Model results for depths greater than those used in the training data, approximately 3500 m, should be used with caution.

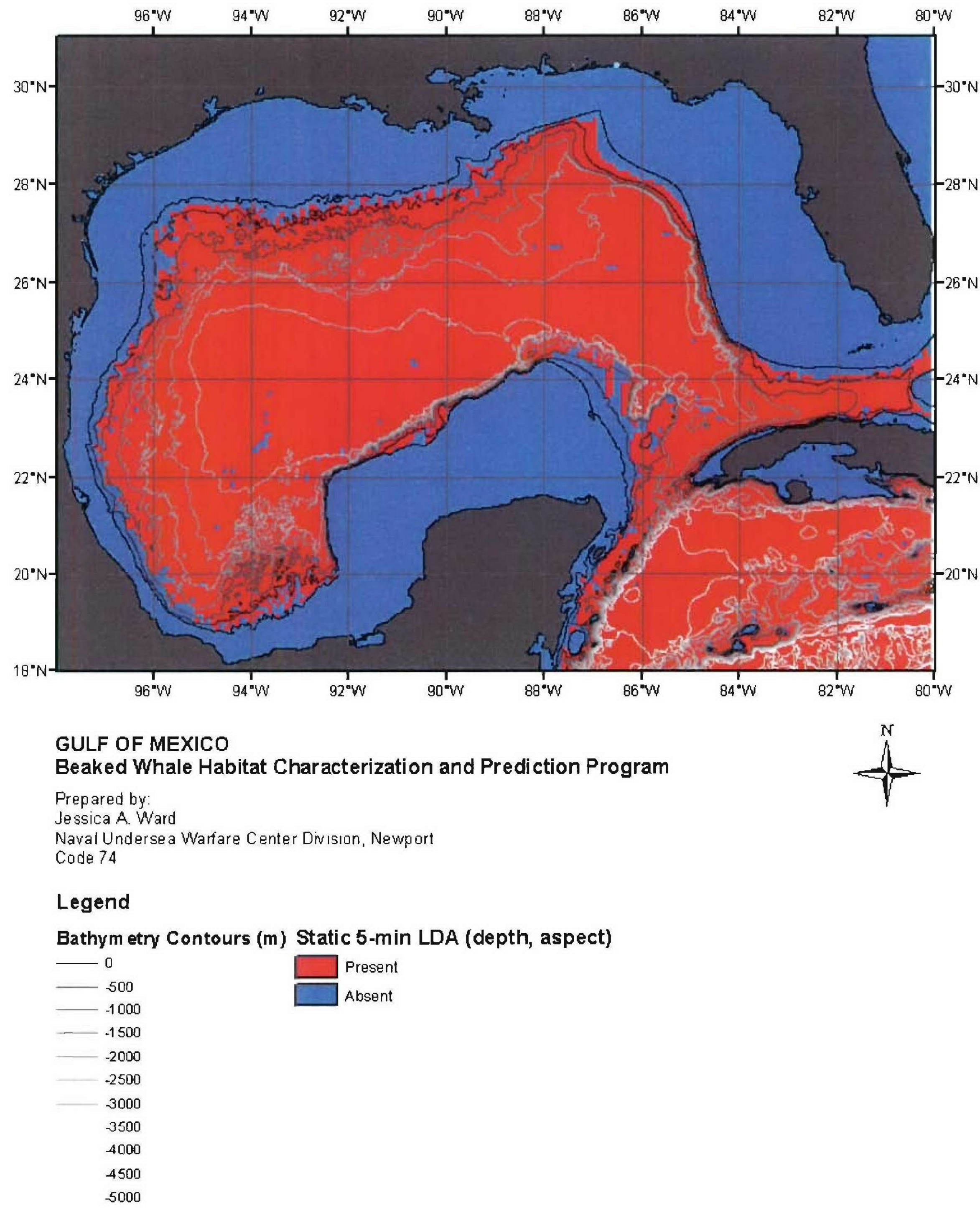


Figure 10. GOM 5-Minute Resolution Static LDA Predicted Habitat

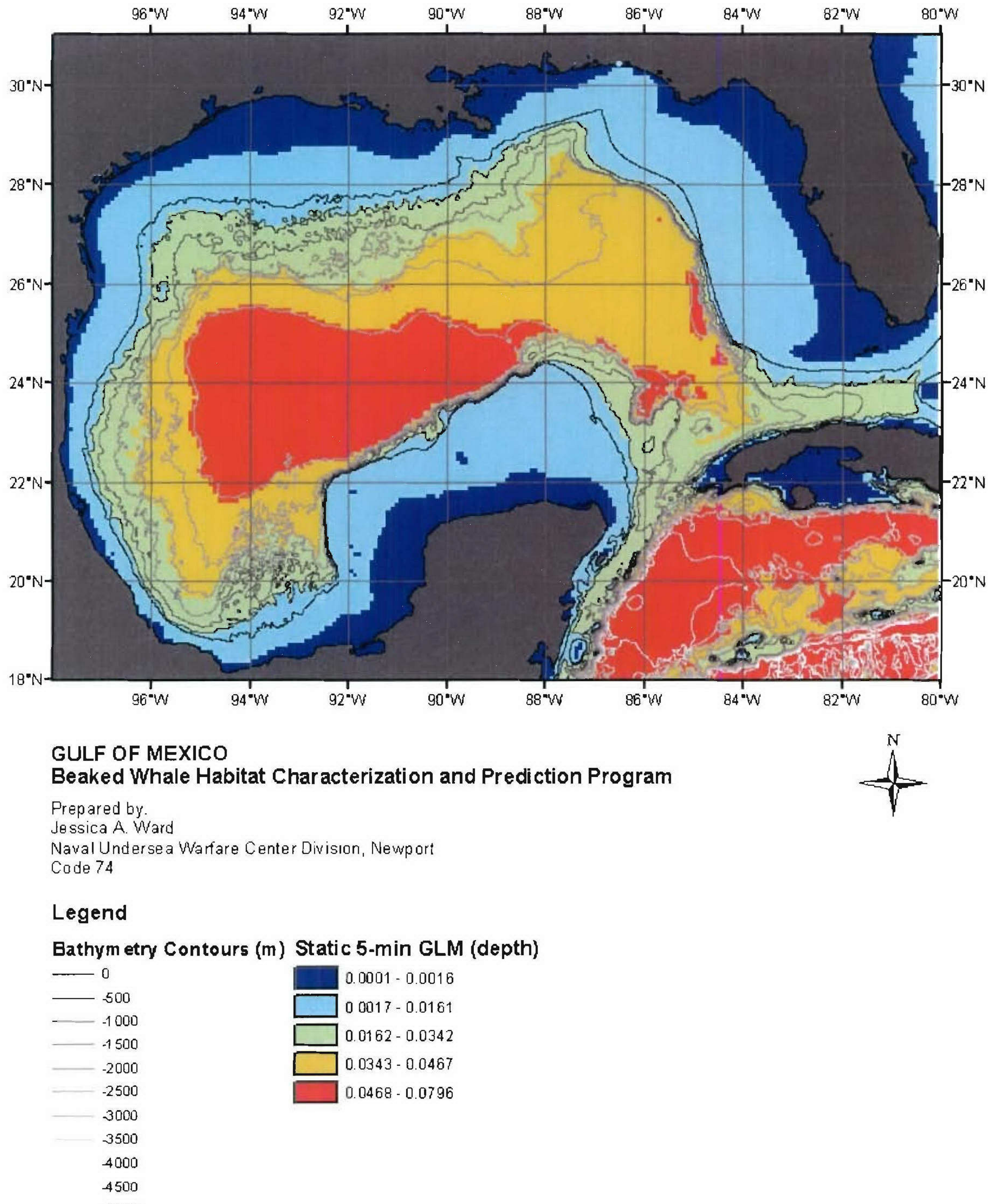


Figure 11. GOM 5-Minute Resolution GLM Static Predicted Habitat
(Note: GLM values greater than 0.0161 indicate cells classified as present.)

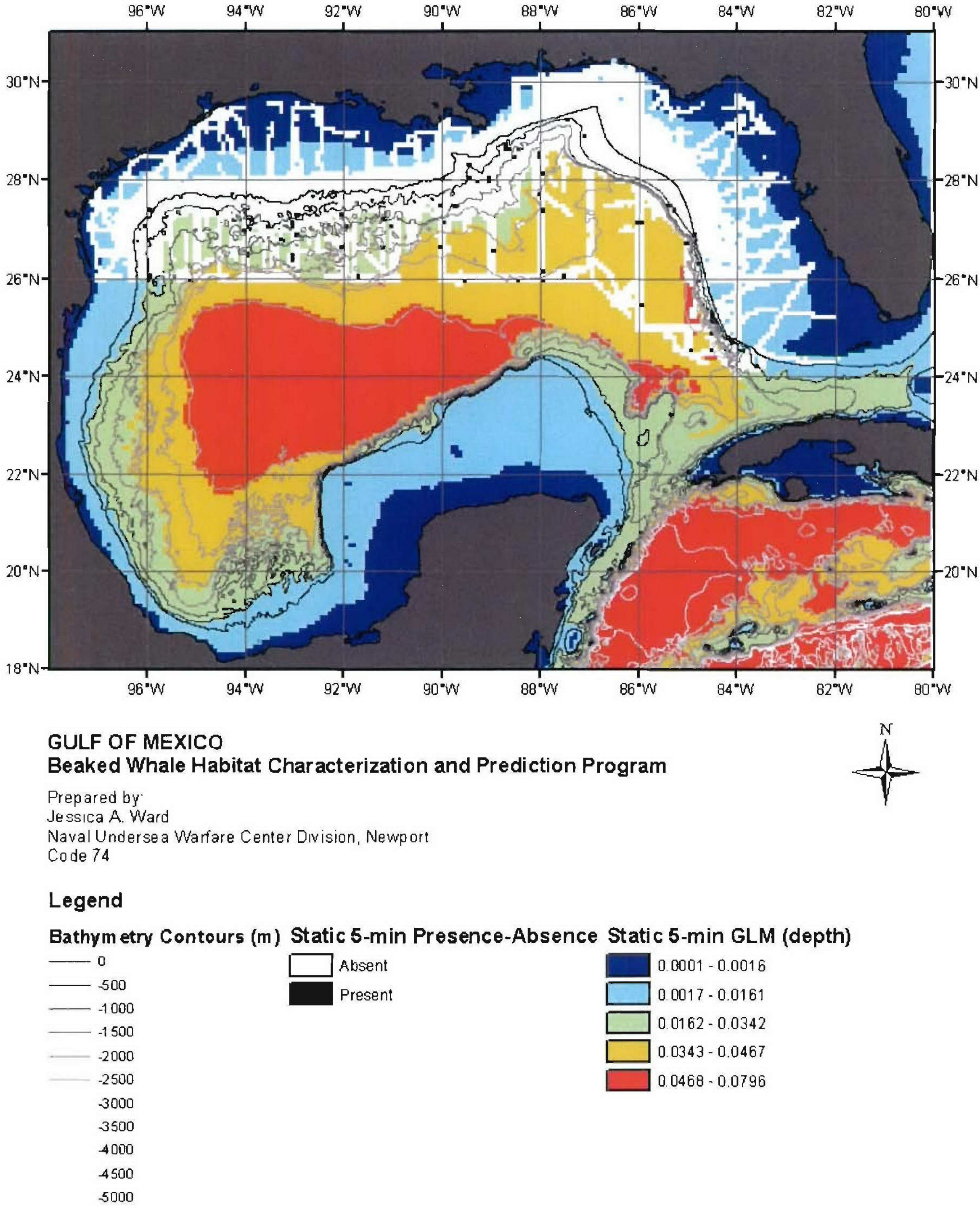


Figure 12. GOM 5-Minute Resolution GLM Static Predicted Habitat with Beaked Whale Presence-Absence Data Overlaid

(Note: GLM values greater than 0.0161 indicate cells classified as present.)

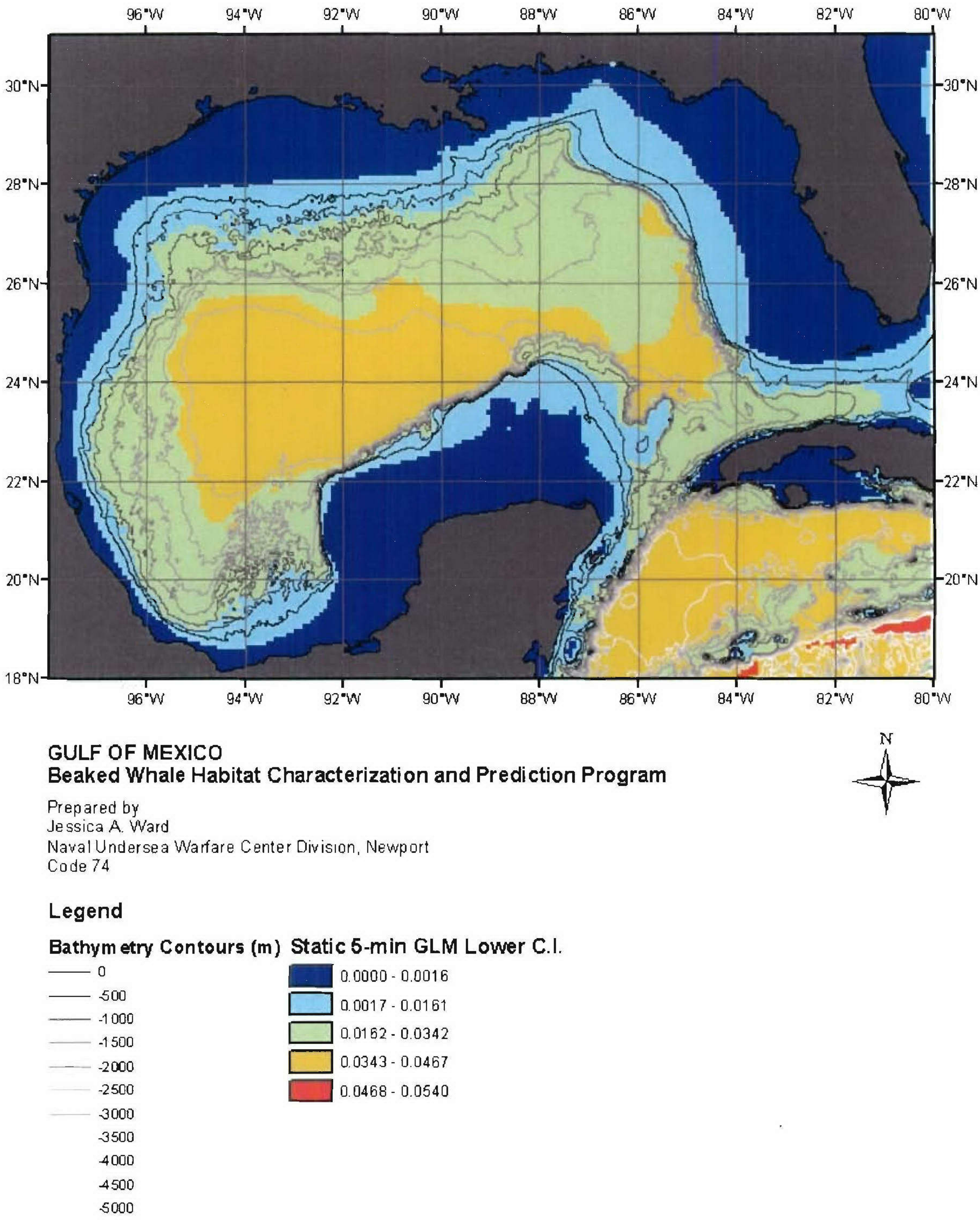


Figure 13. GOM 5-Minute Resolution GLM Static Predicted Habitat, Lower Confidence Interval

(Note: GLM values greater than 0.0161 indicate cells classified as present.)

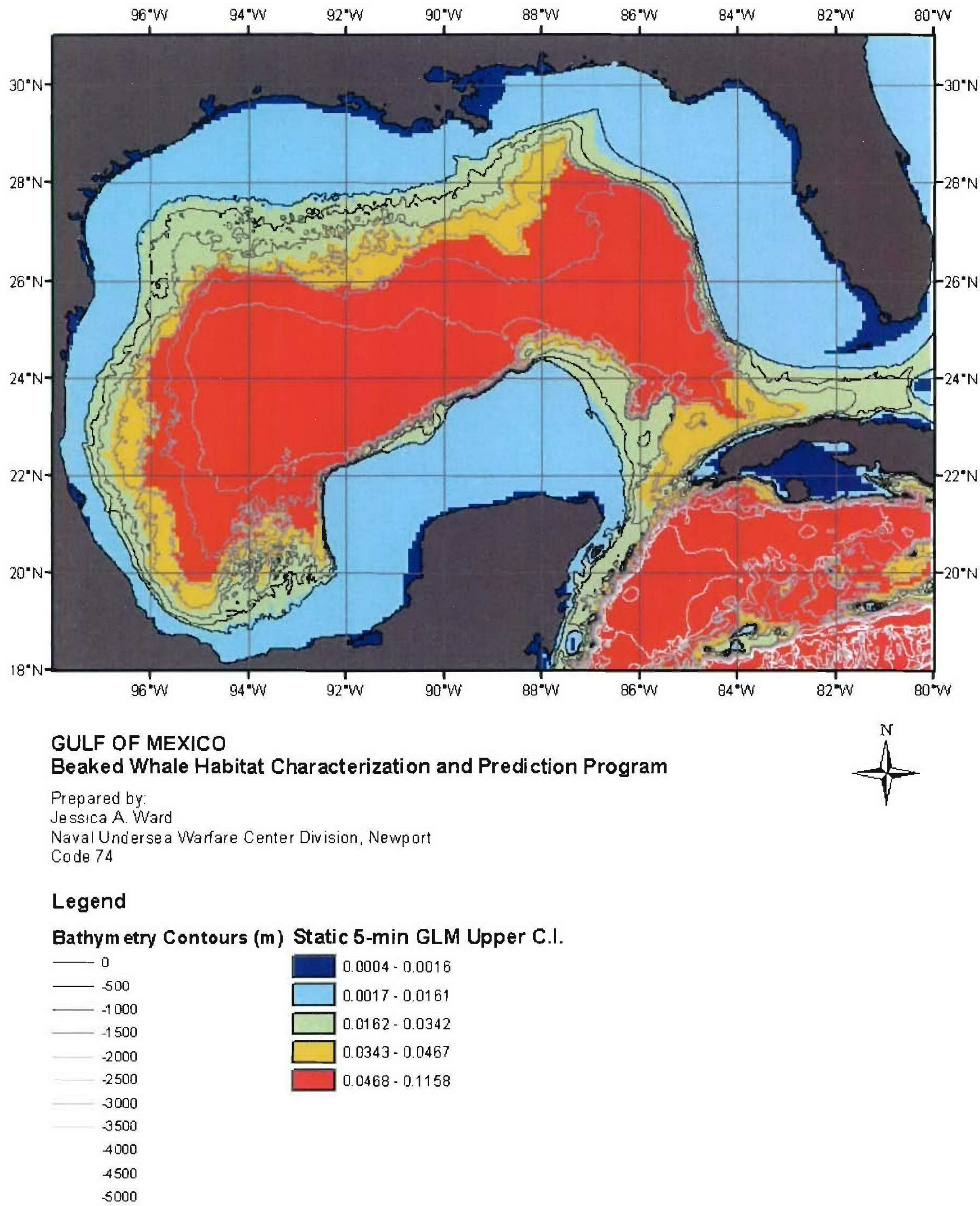


Figure 14. GOM 5-Minute Resolution GLM Static Predicted Habitat, Upper Confidence Interval

(Note: GLM values greater than 0.0161 indicate cells classified as present.)

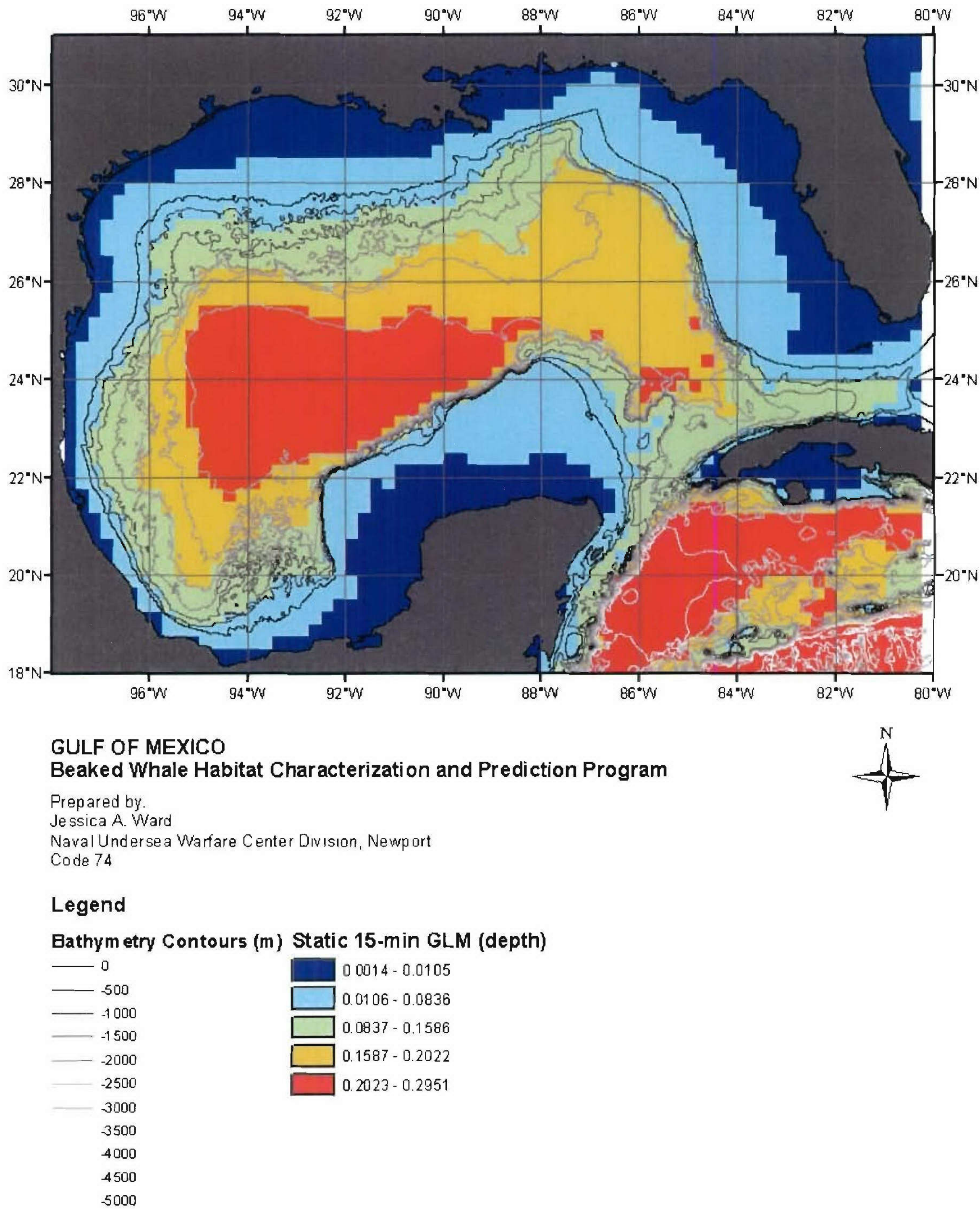


Figure 15. GOM 15-Minute Resolution GLM Static Predicted Habitat
(Note: GLM values greater than 0.0836 indicate cells classified as present.)

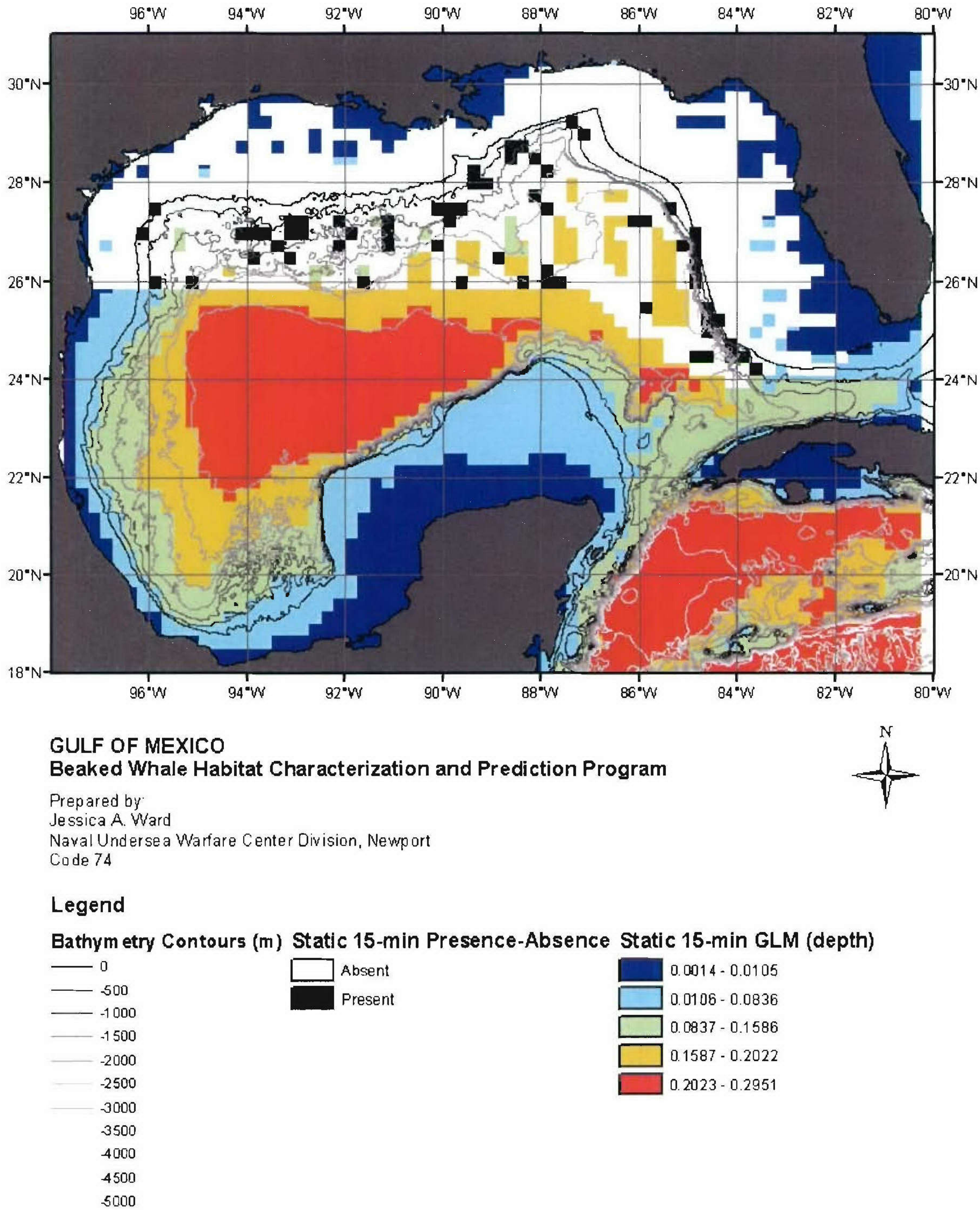


Figure 16. GOM 15-Minute Resolution GLM Static Predicted Habitat with SPUE Overlaid

(Note: GLM values greater than 0.0836 indicate cells classified as present.)

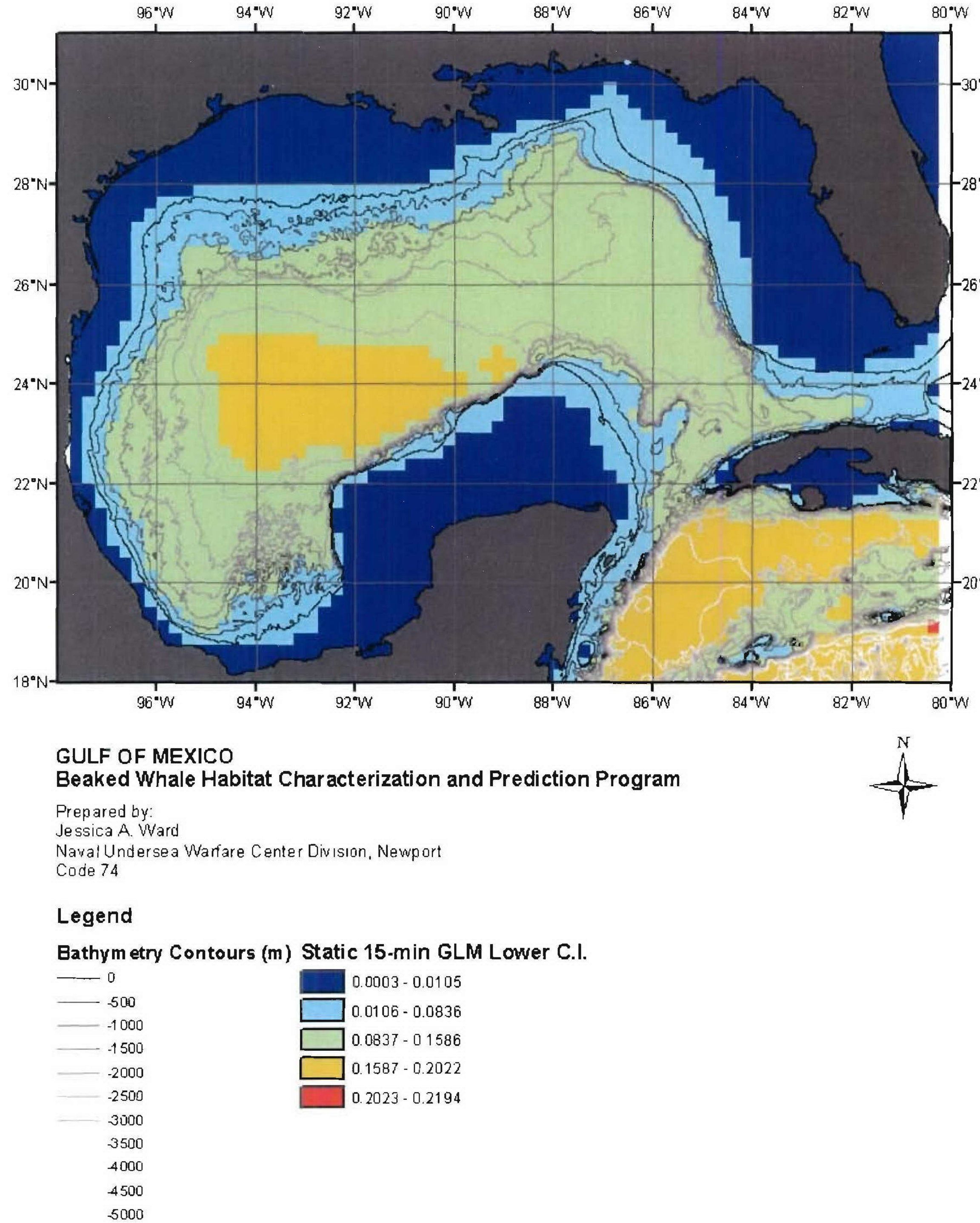


Figure 17. GOM 15-Minute Resolution GLM Static Predicted Habitat, Lower Confidence Interval

(Note: GLM values greater than 0.0836 indicate cells classified as present.)

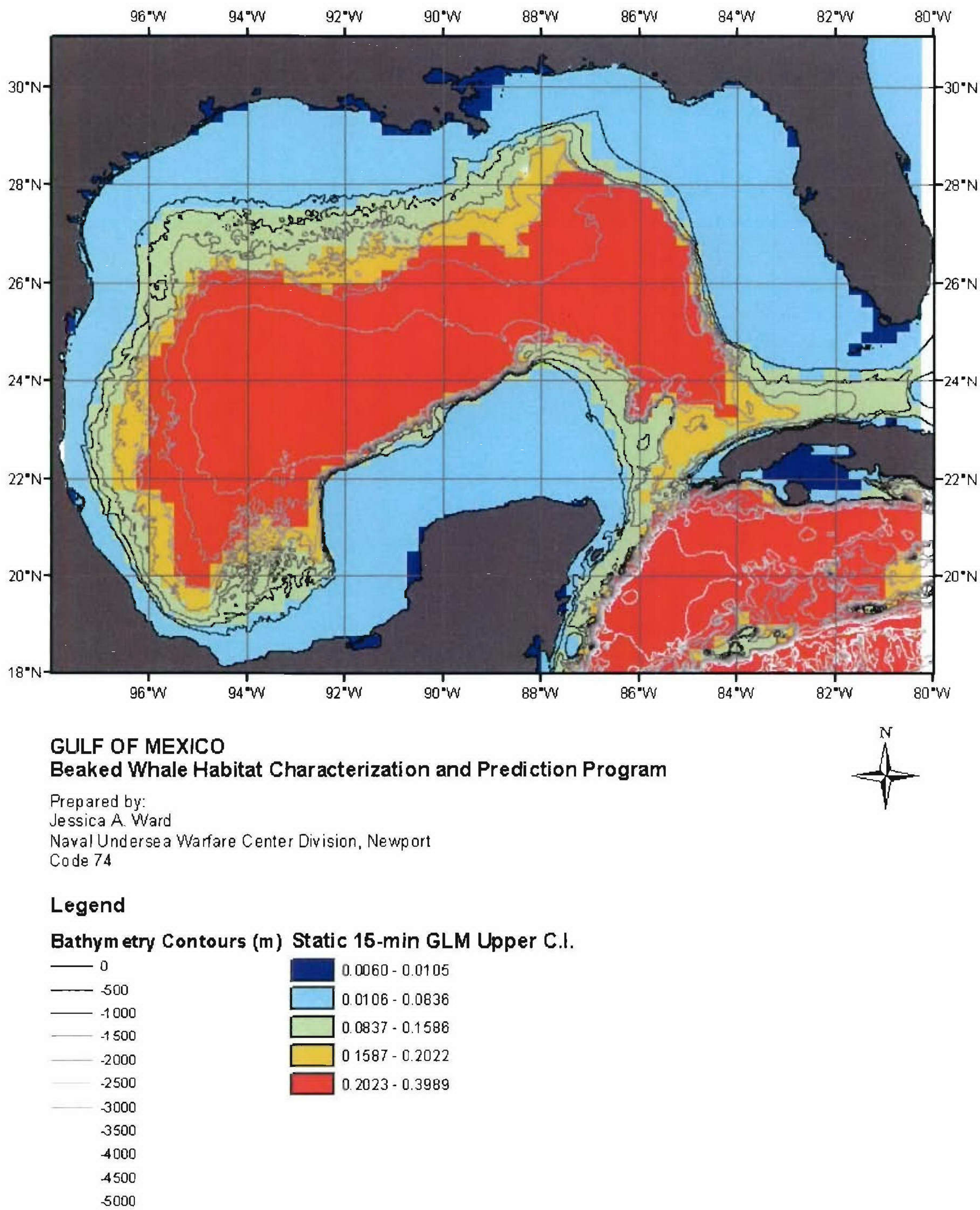


Figure 18. GOM 15-Minute Resolution GLM Static Predicted Habitat, Upper Confidence Interval

(Note: GLM values greater than 0.0836 indicate cells classified as present.)

Dynamic Analysis

The 12 variables listed in table 8 were used to characterize the weekly environment for each 15-minute cell. These variables are mean depth, maximum difference in depth, slope, standard deviation of slope, mean aspect, standard deviation of aspect, distance to nearest frontal edge, mean frontal frequency, mean SST, standard deviation of SST, mean SSH, and standard deviation of SSH.

Habitat Characterization. Table 8 summarizes the values of 15-minute cells in which beaked whales were present. While transforming the variables did bring them closer to a univariate normal distribution, none passed either the Lilliefors or Jarque-Bera test for goodness-of-fit to a normal distribution ($P < 0.05$). Mean slope and maximum change in depth and mean slope and slope standard deviation were correlated for both the transformed and untransformed data sets ($r > 0.50$). Mean aspect and aspect standard deviation were also correlated for the transformed data ($r > 0.50$). The values of cells with beaked whales present differed significantly from those with beaked whales absent for the following variables (Kolmogrov-Smirnov test, $P < 0.05$): mean depth, maximum change in depth, mean slope, standard deviation of slope, standard deviation of aspect, frontal frequency mean SST, and mean SSH. The distribution of values for cells with beaked whales present is shown in figure 19.

Table 8. Habitat Characteristics of 15-Minute Cells from Dynamic Analysis with Beaked Whales Present in the GOM (N = 44)

Variable	Units	Minimum	Maximum	Mean	Standard Deviation
1. Depth (mean)	m	670.63	3455.60	1912.85	842.69
2. Depth (max. Δ)	m	38.75	3087.80	997.65	928.47
3. Slope (mean)	degrees	0.07	6.84	2.04	1.90
4. Slope (std dev)	degrees	0.01	6.07	1.44	1.50
5. Aspect (mean)	degrees	106.57	266.07	185.17	43.19
6. Aspect (std dev)	degrees	5.94	105.07	45.95	27.66
7. Distance to front	km	0.47	258.19	37.86	47.04
8. Front Freq. (mean)	% occurrence	6.0	50.0	17.0	11.0
9. SST (mean)	°F	22.56	30.32	26.70	1.79
10. SST (std dev)	°F	0.15	2.63	0.42	0.39
11. SSH (mean)	cm	–28.17	33.40	–2.87	10.86
12. SSH (std dev)	cm	0.27	4.15	1.19	0.77

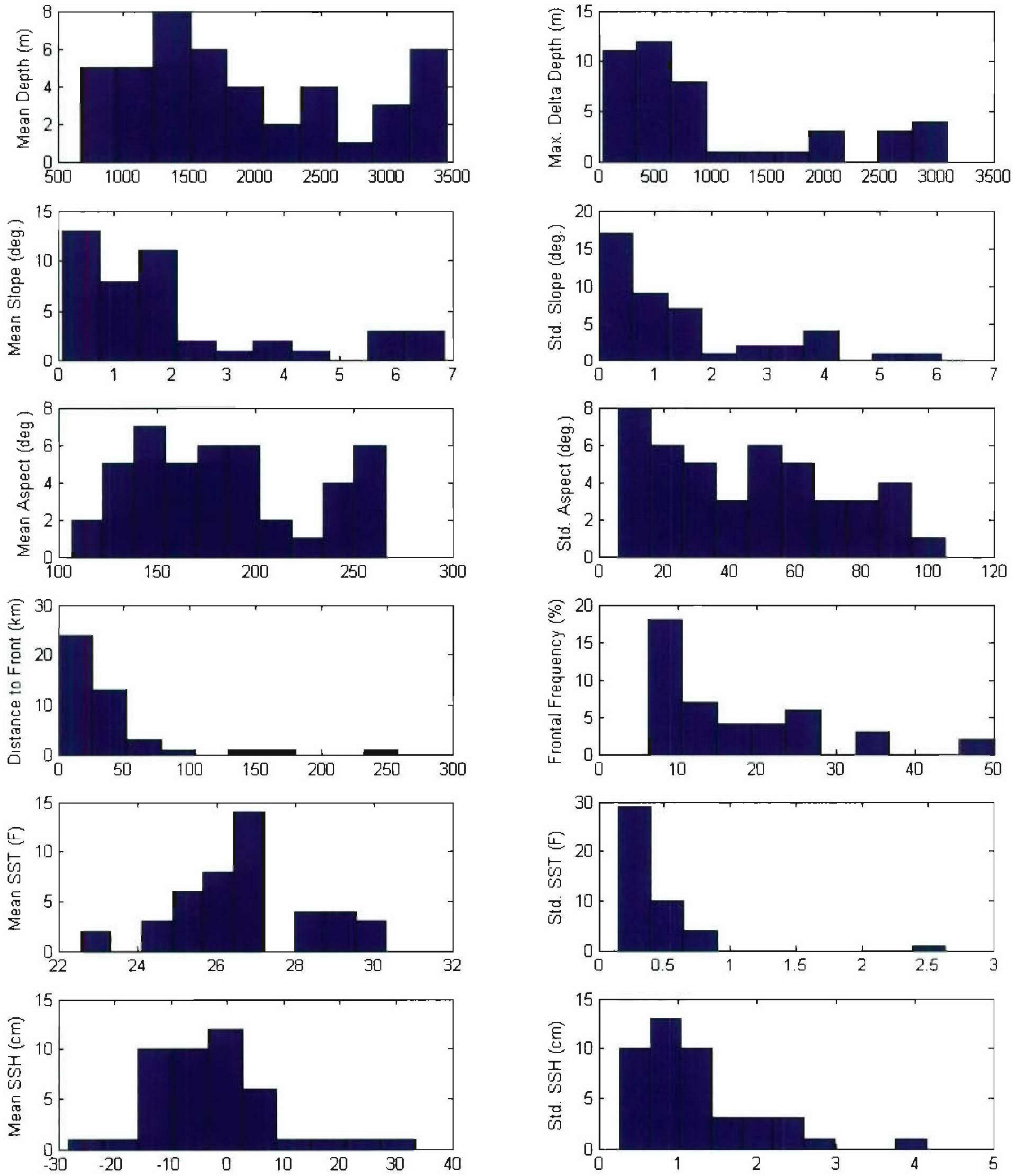


Figure 19. Histograms of Environmental Variables of Cells with Beaked Whales Present in the GOM

(Note: Label along each histogram applies to x-axis, y-axis equals number of observations)

Classification Effectiveness. The optimal variable combination for each type of statistical model based on the mean correct CR is presented in table 9. The optimal GLM variable combination was determined using all possible variable combinations as opposed to a forward step-wise method. The GLM and LDA models produced similar classification effectiveness results; however, the GLM method required only five environmental variables as opposed to the eight required by the LDA method. Therefore, GLM (using mean depth, maximum change in depth, standard deviation of aspect, frontal frequency, and mean SST) is the recommended dynamic model for the GOM. Parsing the data by season was also evaluated, but this resulted in reduced classification effectiveness.

Table 9. GOM Dynamic Model Classification Effectiveness Results

Model	Box-Cox Trans.	Variables	$N_{present}$	% Present Correct	N_{absent}	% Absent Correct	Mean % Correct
LDA	Yes	Mean depth, max. Δ depth, std. slope, std. aspect, mean SST	44	95.45	3088	64.93	80.19
GLM	Yes	Mean depth, max. Δ slope, std. aspect, mean frontal freq., mean SST	44	95.45	3088	65.07	80.26

Habitat Prediction. The optimal GLM classification method was identified and applied to the entire GOM study area to produce a broader geographic estimation of habitat (figures 20 and 24). In addition to the static variables, the model included SST and frontal frequency as a means of capturing time-variant environmental changes in habitat. This model accurately predicted the known habitat for 95.5% of the 15-minute cells known to have beaked whales present. This is demonstrated for two different weekly periods in figures 20 through 27. The corresponding SST and SSH anomaly data are also shown for comparison.

The addition of dynamic variables results in a more intuitive prediction of habitat. Rather than simply increasing with depth, as in the static model, the probability of beaked whale presence reaches a maximum along the slope and decreases toward the Continental Shelf and deep abyssal plain.

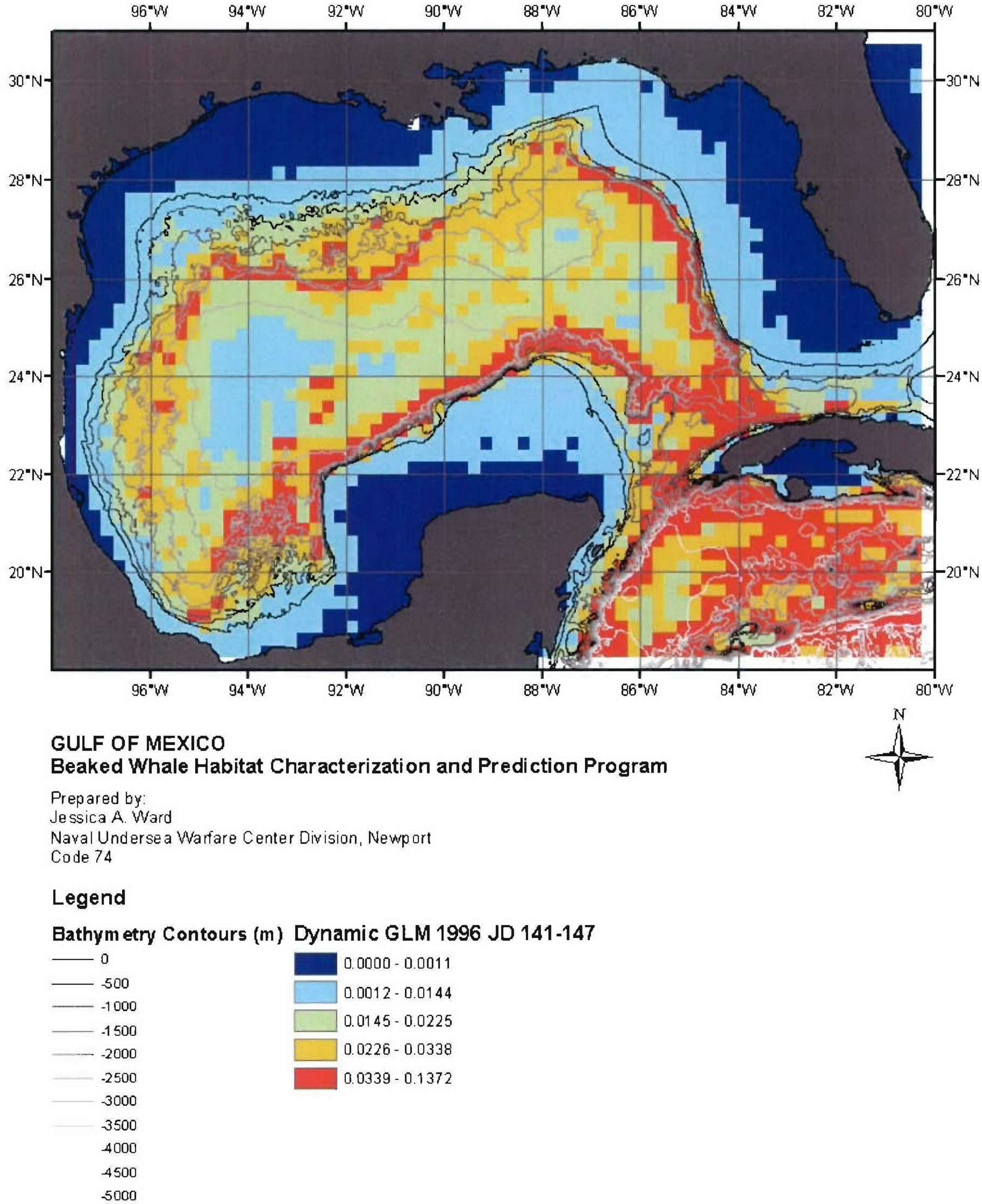


Figure 20. GOM 15-Minute Resolution GLM Dynamic Predicted Habitat for 1996, Julian Days 141-147

(Note: GLM values greater than 0.0144 indicate cells classified as present.)

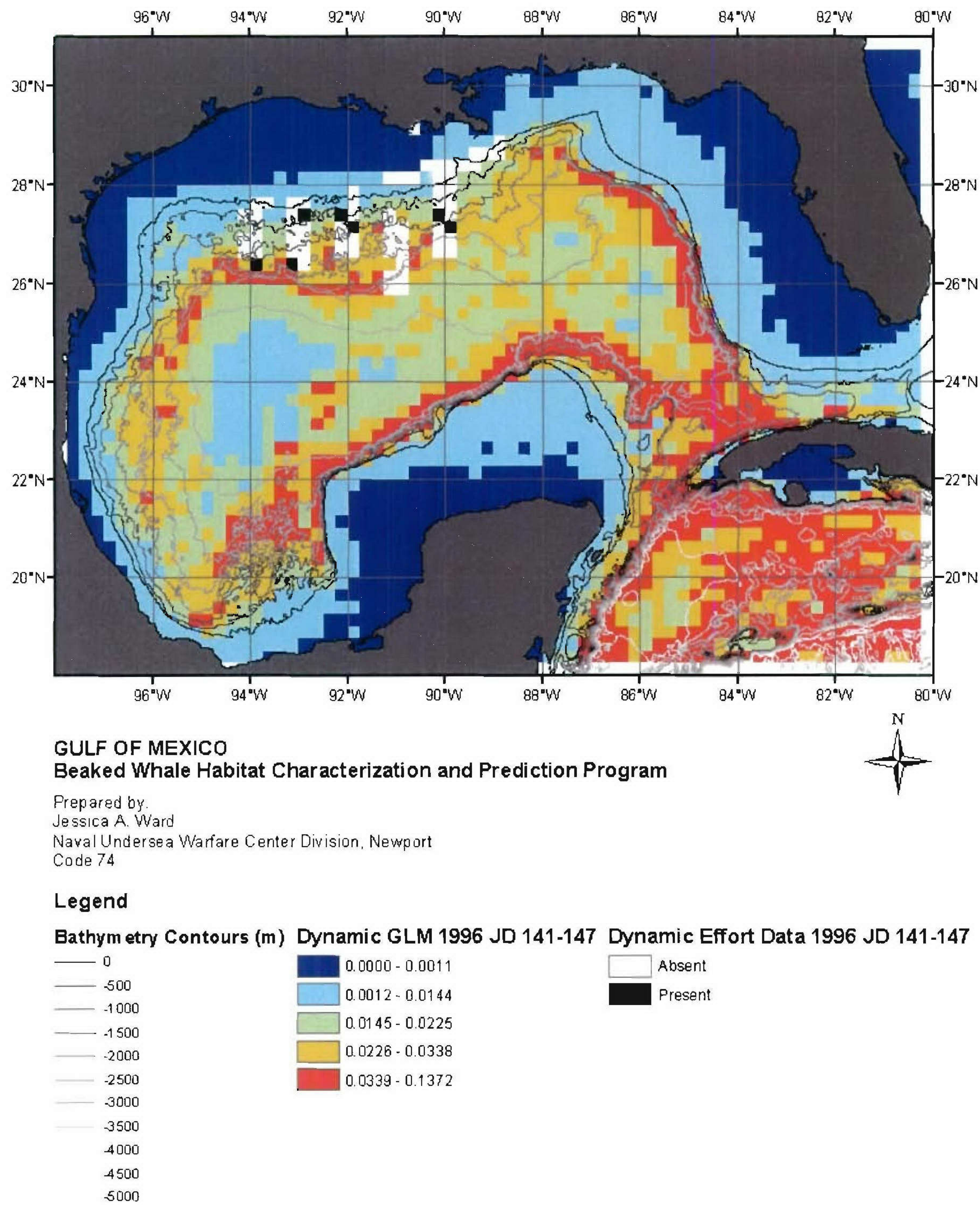


Figure 21. GOM 15-Minute Resolution GLM Dynamic Predicted Habitat for 1996, Julian Days 141-147 with Effort Data Overlaid

(Note: GLM values greater than 0.0144 indicate cells classified as present.)

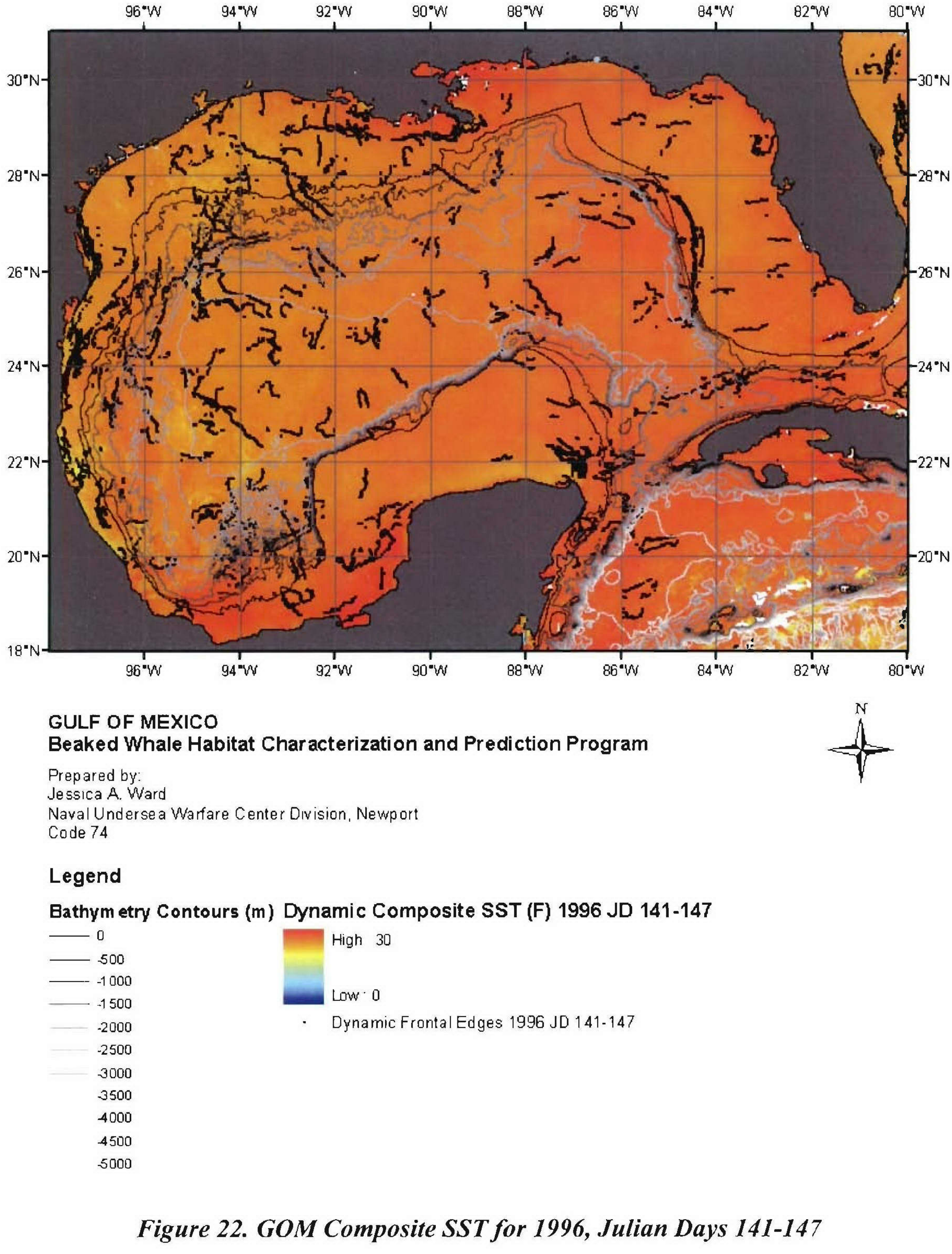


Figure 22. GOM Composite SST for 1996, Julian Days 141-147

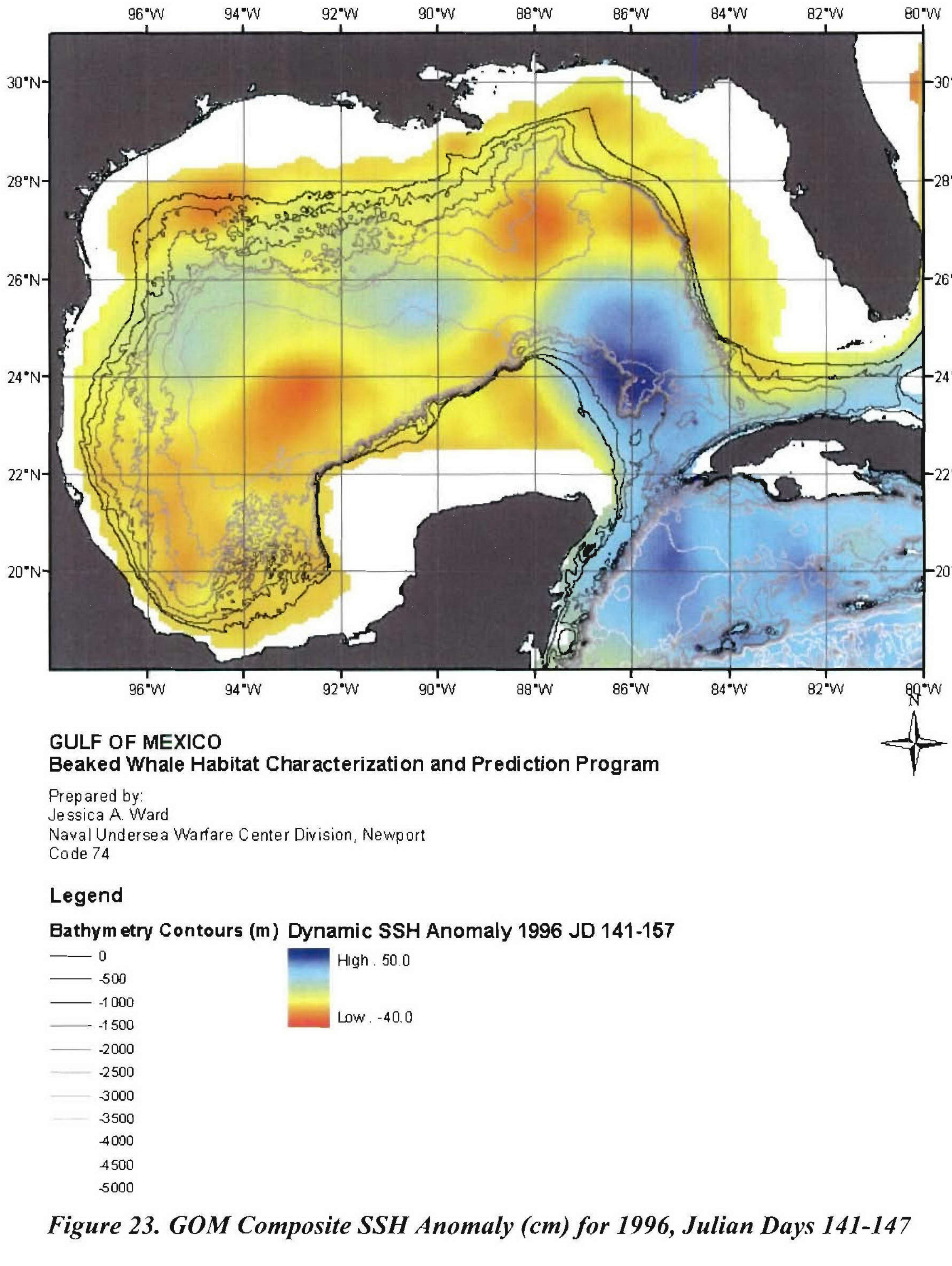


Figure 23. GOM Composite SSH Anomaly (cm) for 1996, Julian Days 141-147

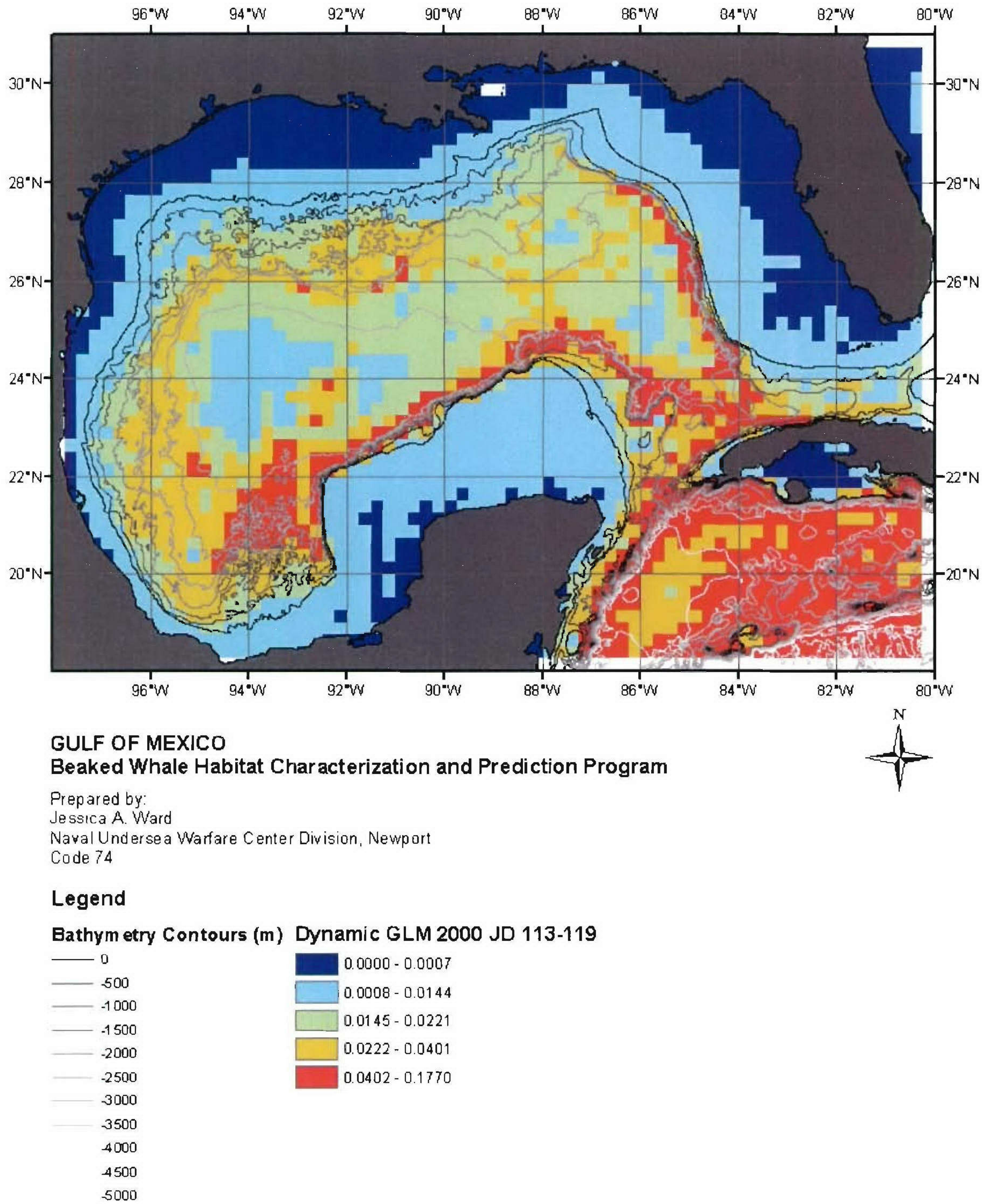


Figure 24. GOM 15-Minute Resolution GLM Dynamic Predicted Habitat for 2000, Julian Days 113-119

(Note: GLM values greater than 0.0144 indicate cells classified as present.)

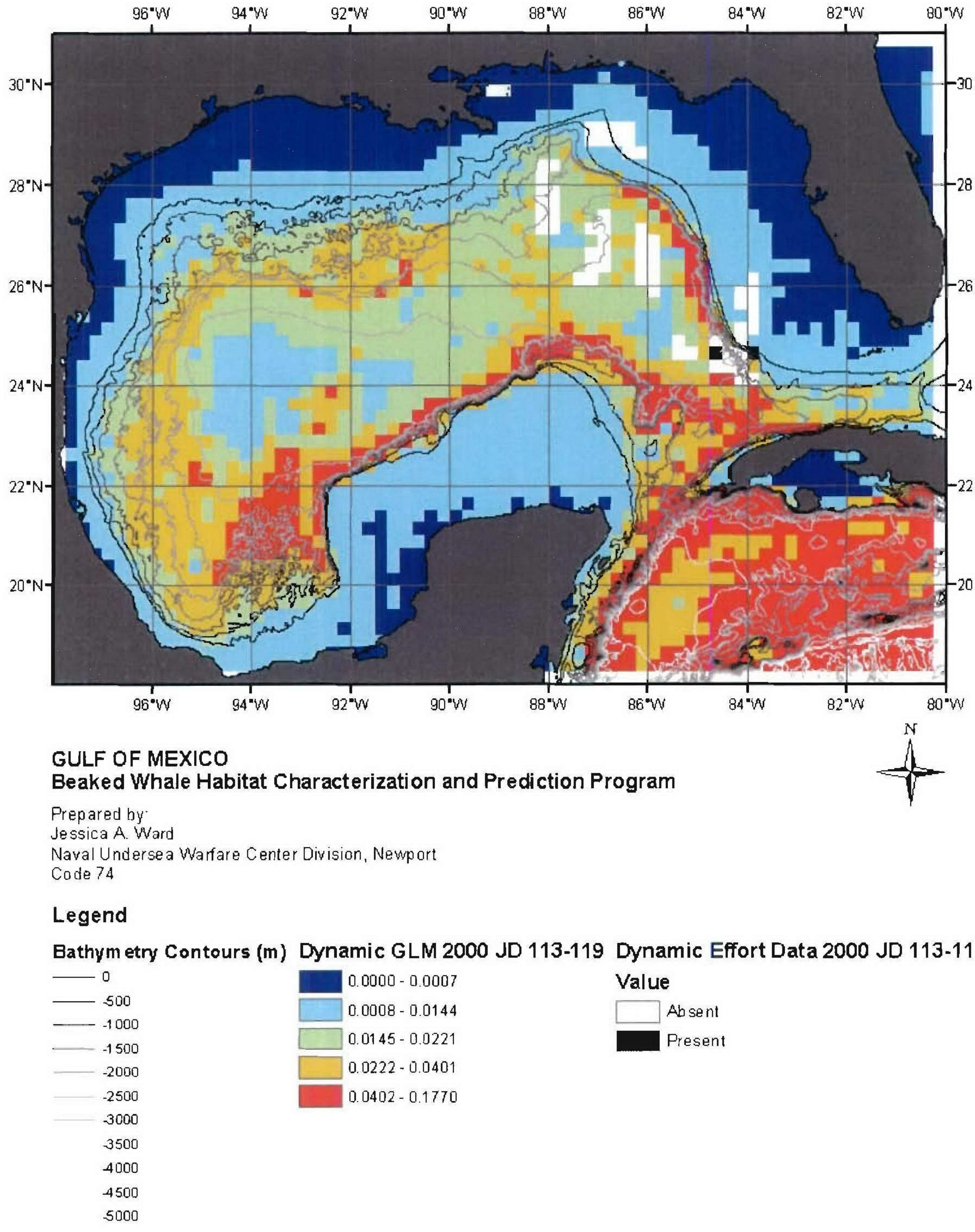


Figure 25. GOM 15-Minute Resolution GLM Dynamic Predicted Habitat for 2000, Julian Days 113-119 with Effort Data Overlaid

(Note: GLM values greater than 0.0144 indicate cells classified as present.)

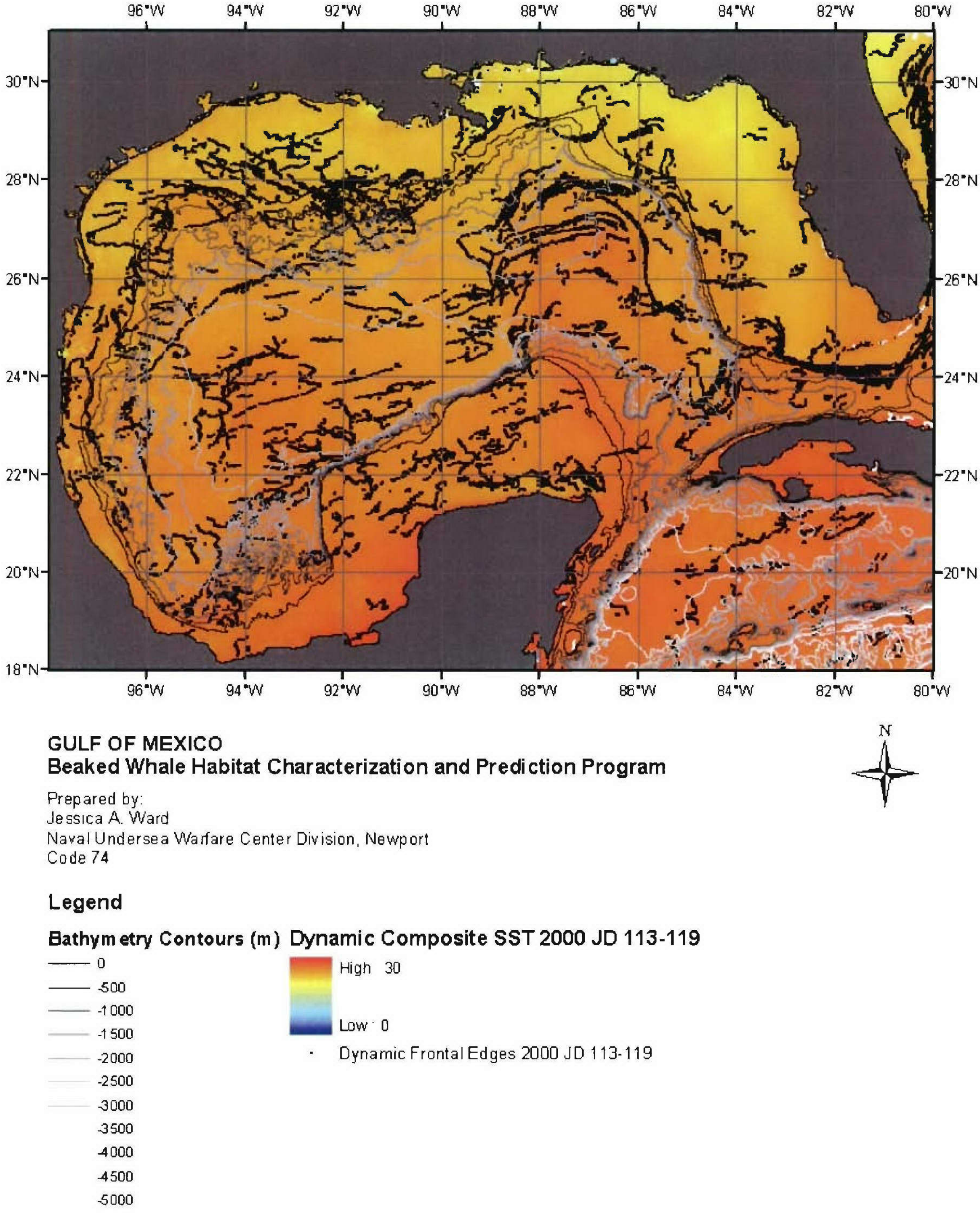


Figure 26. GOM Composite SST for 2000, Julian Days 113-119

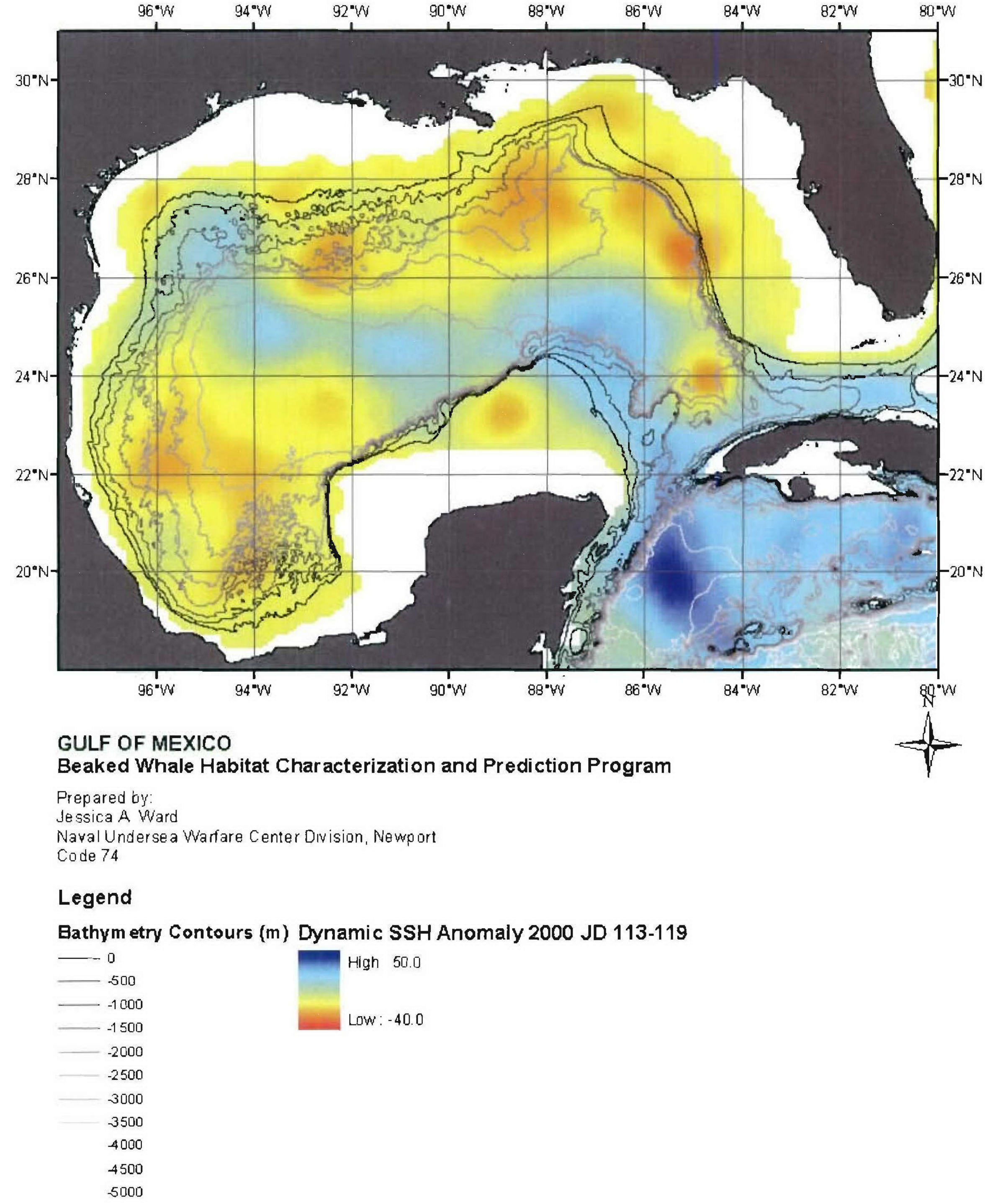


Figure 27. GOM Composite SSH Anomaly (cm) for 2000, Julian Days 113-119

3.3 SOUTHEAST UNITED STATES STUDY AREA

Beaked whale data available for the SEUS study area included the following events (number of individuals indicated in parentheses): 1 (2) mass stranding, 51 (51) single strandings, 151 (171) unclassified strandings, 45 unknown, 1 (1) bycatch, 10 (35) visual sightings, and 52 (132) visual shipboard sightings. Species identification for the sighting data was typically limited to genus, but in those cases where a more detailed identification was made it included *Mesoplodon sp.*, *Mesoplodon densirostris*, *Mesoplodon mirus*, and *Ziphius cavirostris* (figures 28 through 30). Stranding data classification was limited to genus with the exception of *Ziphius sp.* (figure 28).

Static Analysis

The mean depth, slope, aspect, and standard deviation of the aspect for each cell were used to characterize and predict habitat at cell resolutions of 5, 10 and 15 minutes (figures 28 through 30).

Habitat Characterization. Table 10 summarizes the values of the 5-minute cells in which beaked whales were present. Even when transformed, none of the variables passed either the Lilliefors or Jarque-Bera test for goodness-of-fit to a normal distribution ($P < 0.05$). While the untransformed variables were uncorrelated, the transformed variable models for the mean depth and mean slope were correlated at all resolutions, and the mean slope and standard deviation of aspect were correlated at 5-minute resolution ($r > 0.5$). For the 5-minute and 10-minute models, the mean depth of cells with beaked whales present differed significantly from those with beaked whales absent (Kolmogorov-Smirnov test, $P < 0.05$).

Table 10. Habitat Characteristics of 5-Minute Cells with Beaked Whales Present in SEUS (N = 6)

Variable	Minimum	Maximum	Mean	Standard Deviation
Mean depth (m)	642.82	4480.40	1793.34	1436.48
Mean slope (°)	0.19	2.62	0.86	0.91
Mean aspect (°)	90.43	252.20	141.02	57.26
Std dev of aspect (°)	12.45	80.25	31.08	24.82

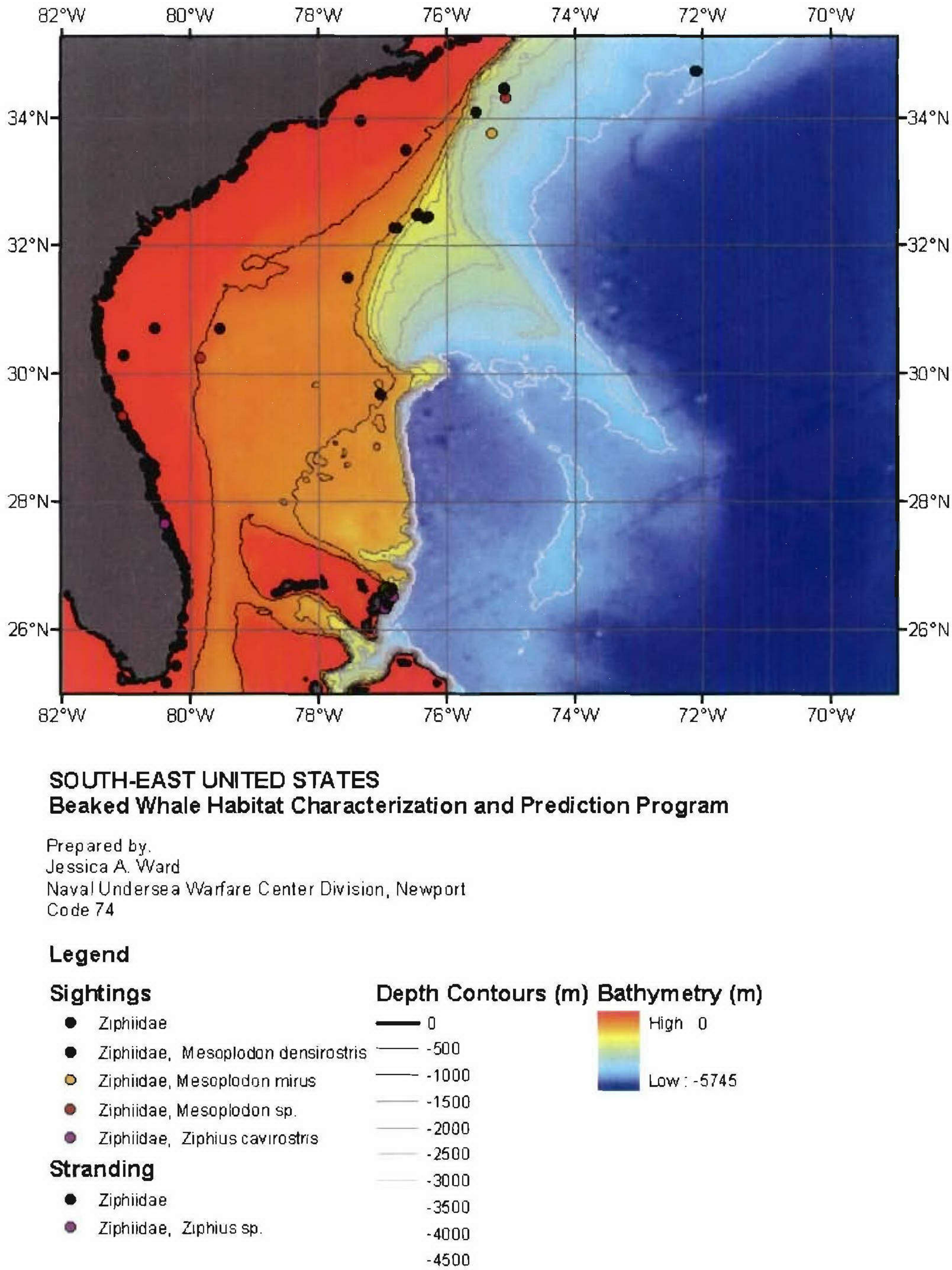


Figure 28. SEUS Sightings and Strandings Overlaid on Depth Data

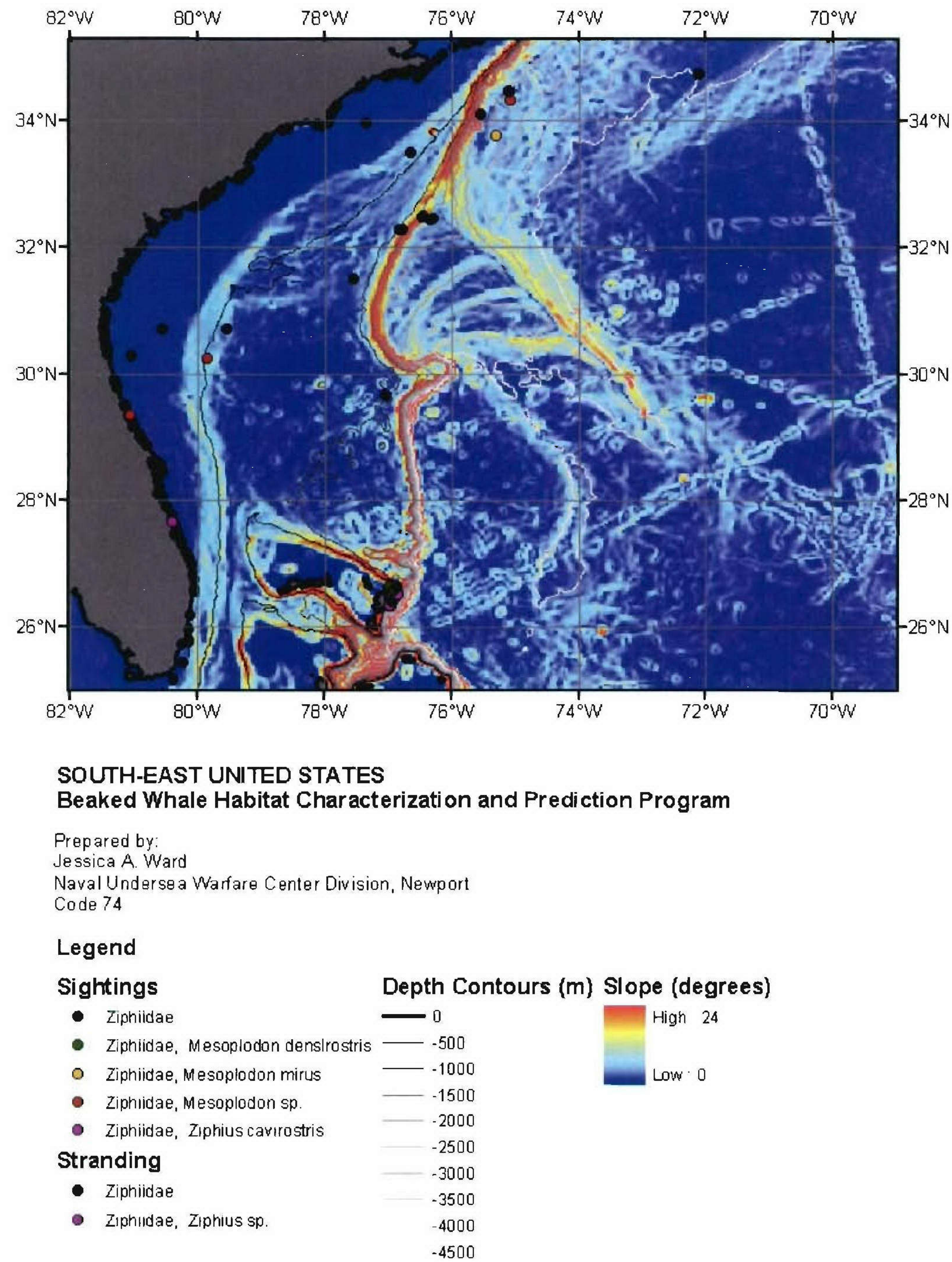


Figure 29. SEUS Sightings and Strandings Overlaid on Slope Data

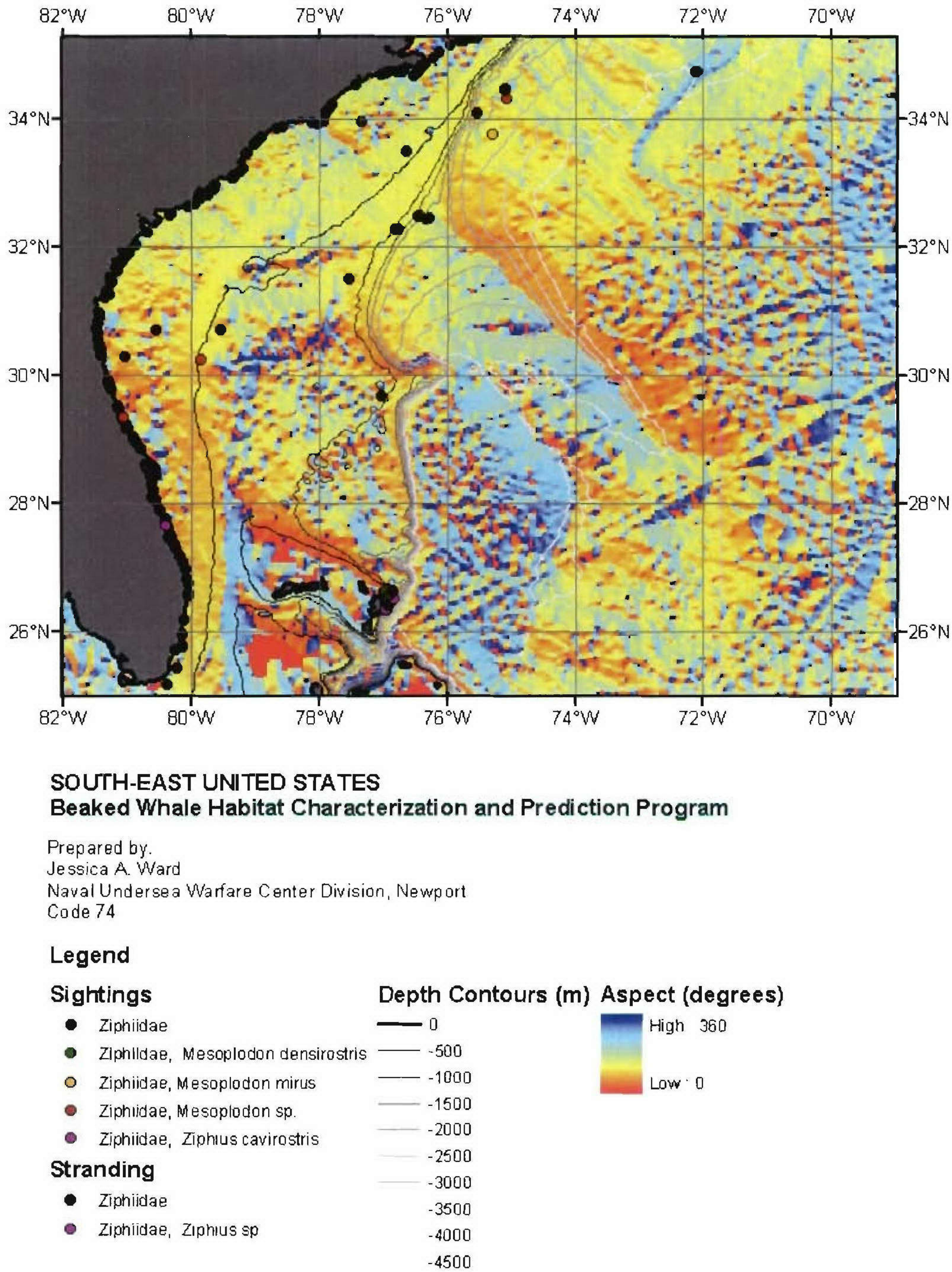


Figure 30. SEUS Sightings and Strandings Overlaid on Aspect Data

Classification Effectiveness. The optimal model for each cell resolution based on the mean correct CR is presented in table 11. In all cases, models based on the transformed data performed better than those based on untransformed data. At the 5-minute resolution, the ENFA model, run in the default mode, had the same correct present CR as that of the optimal LDA model. Few inferences should be drawn from this model due to the small sample size of the cells with beaked whales present and the high standard deviation of the environmental variables from the cells. To increase the sample size of cells with beaked whales present, the ENFA model was applied to the static data set using all available sightings data, both with and without effort.

Table 11. SEUS Static Model Classification Effectiveness Results

Cell Size (min)	Box-Cox Trans.	Model	Variables	$N_{present}$	% Present Correct	N_{absent}	% Absent Correct	Mean % Correct
5	Yes	LDA	Depth, Aspect Std Dev	6	100.0	2095	62.63	81.31
9	Yes	LDA	Depth, Slope, Aspect Std Dev	6	83.3	878	68.91	76.12
15	Yes	LDA	Depth, Aspect	5	60.0	442	64.71	62.53

Habitat Prediction. The optimal classification model identified in table 11 was applied to the entire SEUS study area in order to produce a broader geographic estimation of habitat (figure 31). With few exceptions, all cells deeper than 500 m were classified as potential beaked whale habitat. While the deep ocean basin was classified as potential habitat, this model, due to its linear nature, is not recommended for depths greater than the maximum depth of the survey data used to develop the classification model, i.e., approximately 4500 m (figure 32). Due to the small sample size upon which the model is based, caution should be exercised when using these results for environmental planning purposes.

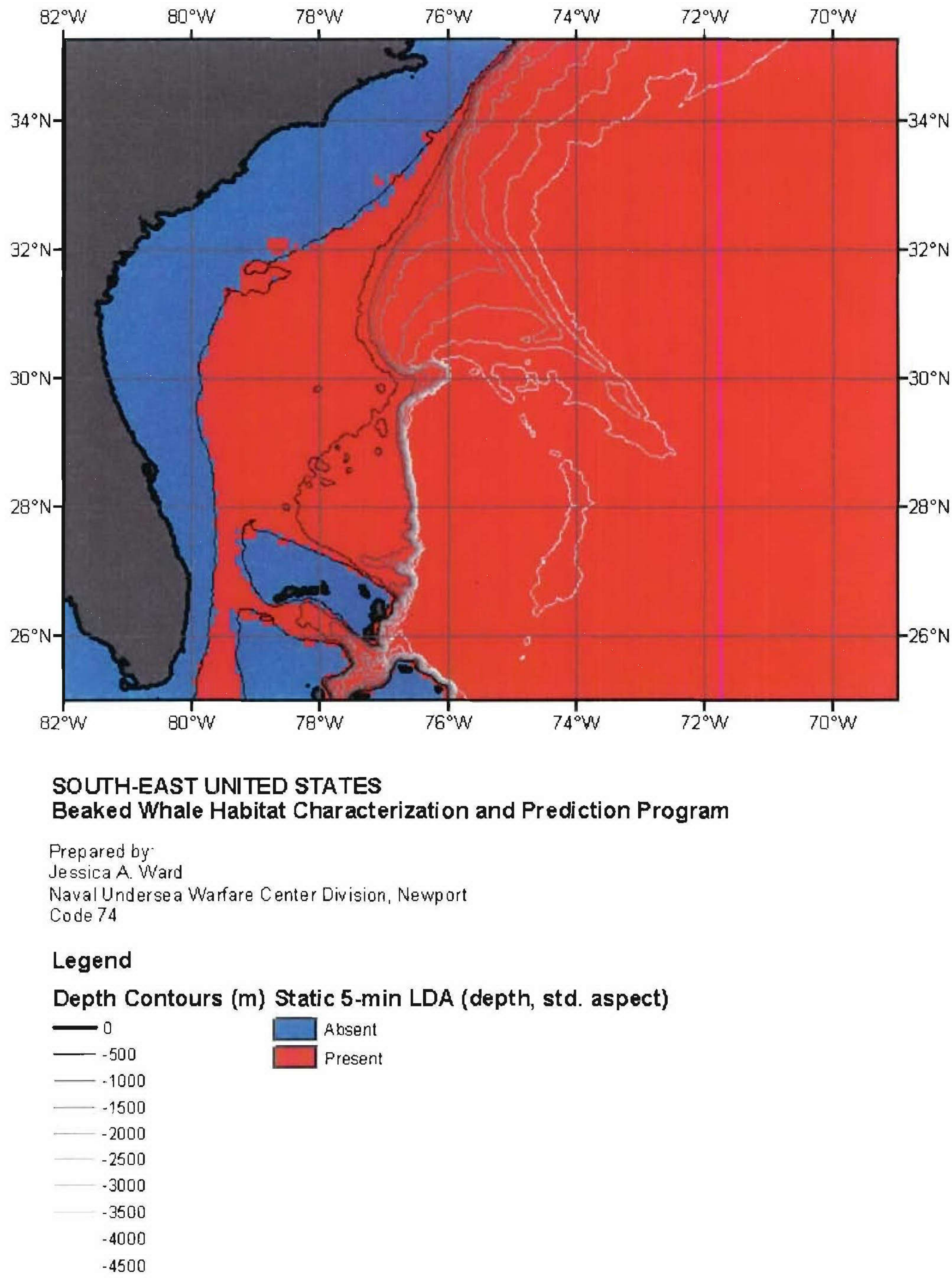


Figure 31. SEUS 5-Minute Resolution Static LDA Predicted Habitat

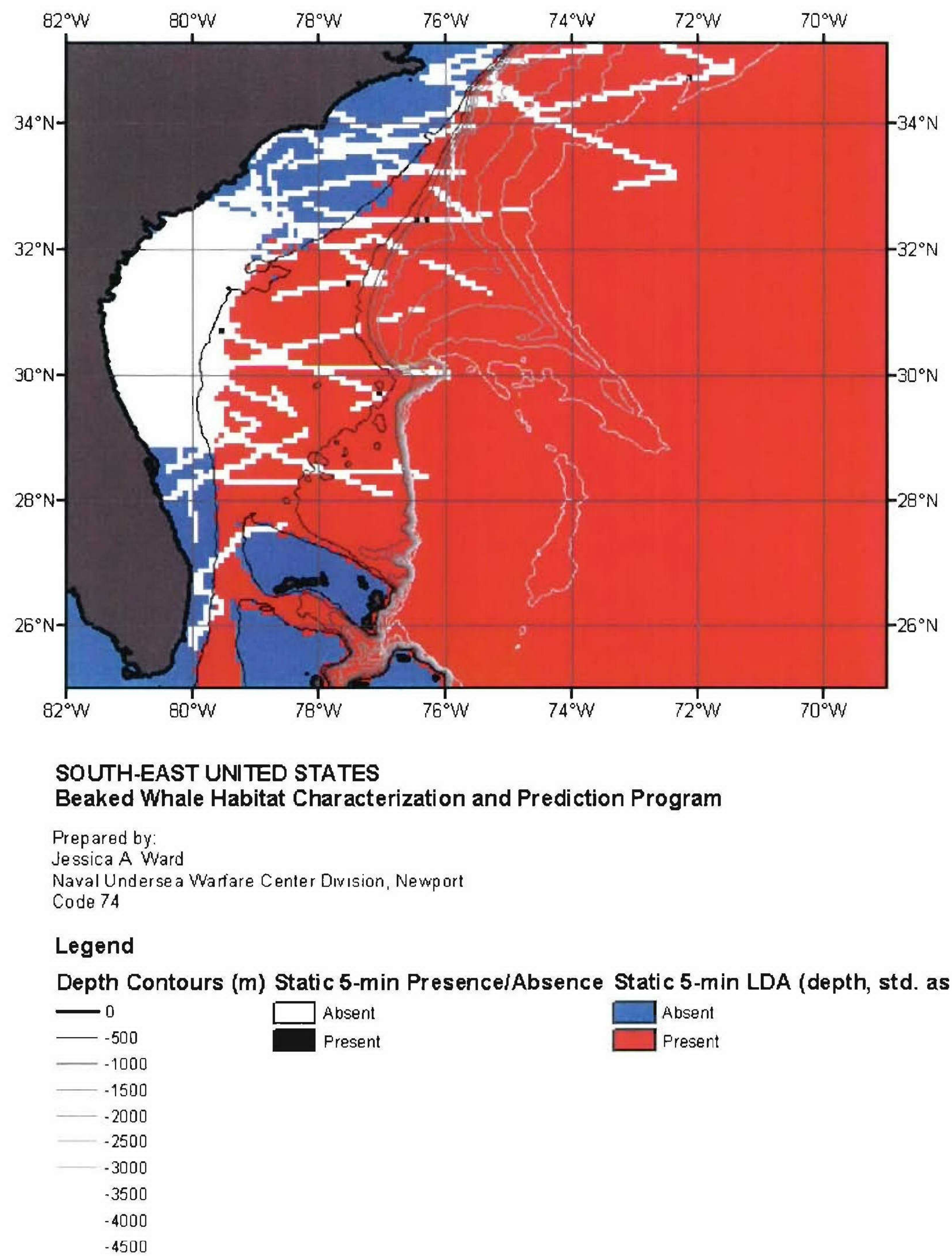


Figure 32. SEUS 5-Minute Resolution Static LDA Predicted Habitat with Beaked Whale Presence/Absence Effort Data Overlaid

Dynamic Analysis

After further limiting the six cells with beaked whales present by the availability of oceanographic data corresponding to the years the survey data were collected, only two cells with beaked whales present remained. This sample size is too small to use as a basis for habitat prediction; therefore, no dynamic habitat characterization results can be completed for the SEUS study area until a larger data set is available.

Sightings-Only Analysis

Due to the small number of sightings available with corresponding effort data, an ENFA analysis was completed utilizing all available sightings, including those without effort data. ENFA models were created for all variable combinations of mean depth, mean slope, mean aspect, and standard deviation of aspect at 5-minute, 9-minute, and 15-minute resolutions. The optimal model used the Box-Cox transformed variables of mean depth and mean aspect at a 9-minute resolution (figure 33). This model had the highest classification effectiveness for correctly predicting beaked whale presence, 83.3 % ($N = 24$ cells known present). This is the suggested model for use in the SEUS study area due to the larger sample size, which is four times that of the static analysis using effort data. The values of the 9-minute cells in which beaked whales were present are summarized in table 12 and figure 34.

Table 12. Habitat Characteristics of 9-Minute Cells with Beaked Whales Present in the SEUS (N = 24)

Variable	Minimum	Maximum	Mean	Std. Deviation
Mean depth (m)	2.76	4483.31	1414.14	1270.94
Mean slope (°)	0.02	10.62	2.28	0.71
Mean aspect (°)	85.36	248.82	125.39	123.20
Std dev of aspect (°)	5.19	87.90	45.17	41.26

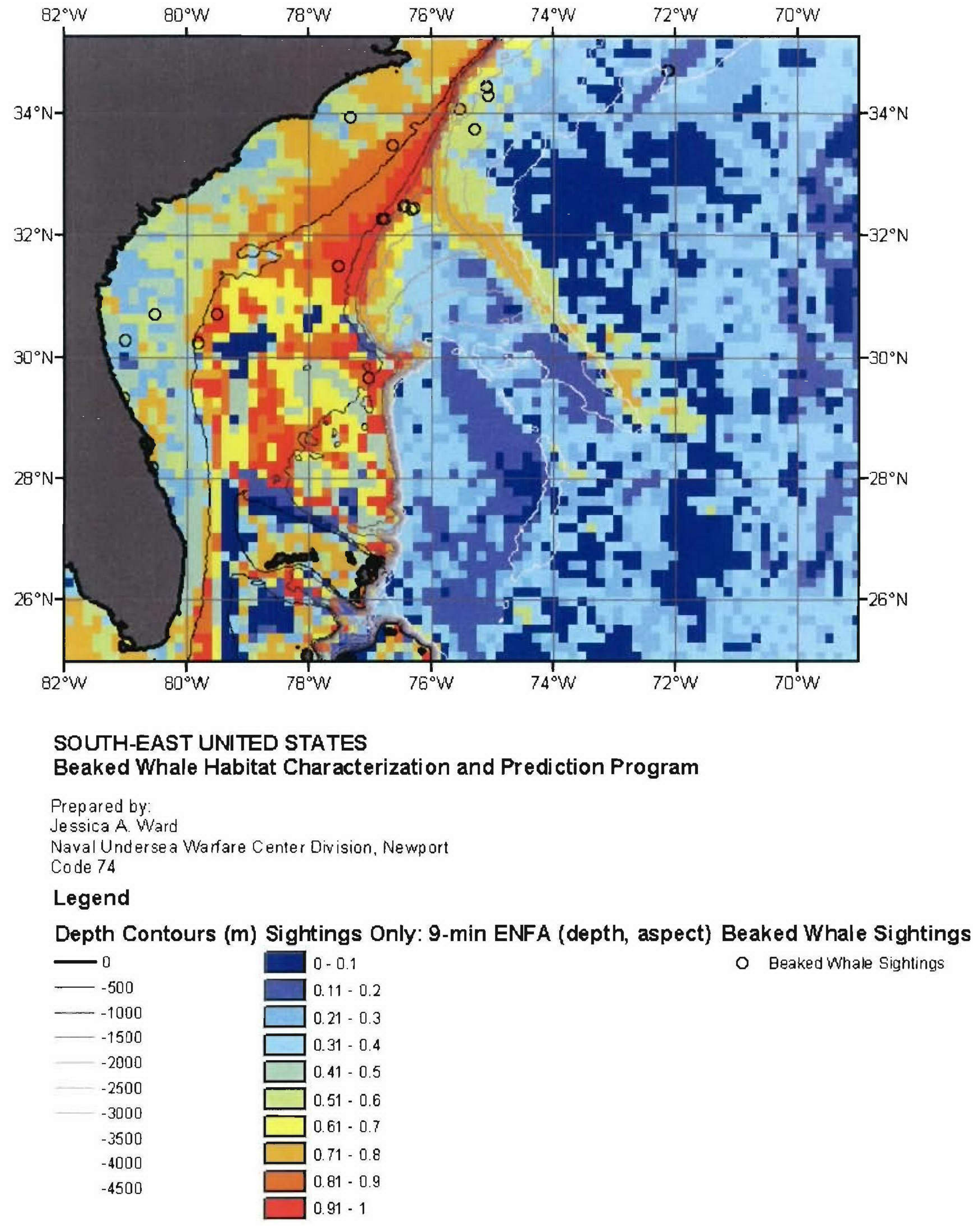


Figure 33. SEUS 9-Minute Resolution ENFA Sightings-Only Predicted Habitat
(Note: ENFA values greater than 0.5 indicate potential beaked whale habitat.)

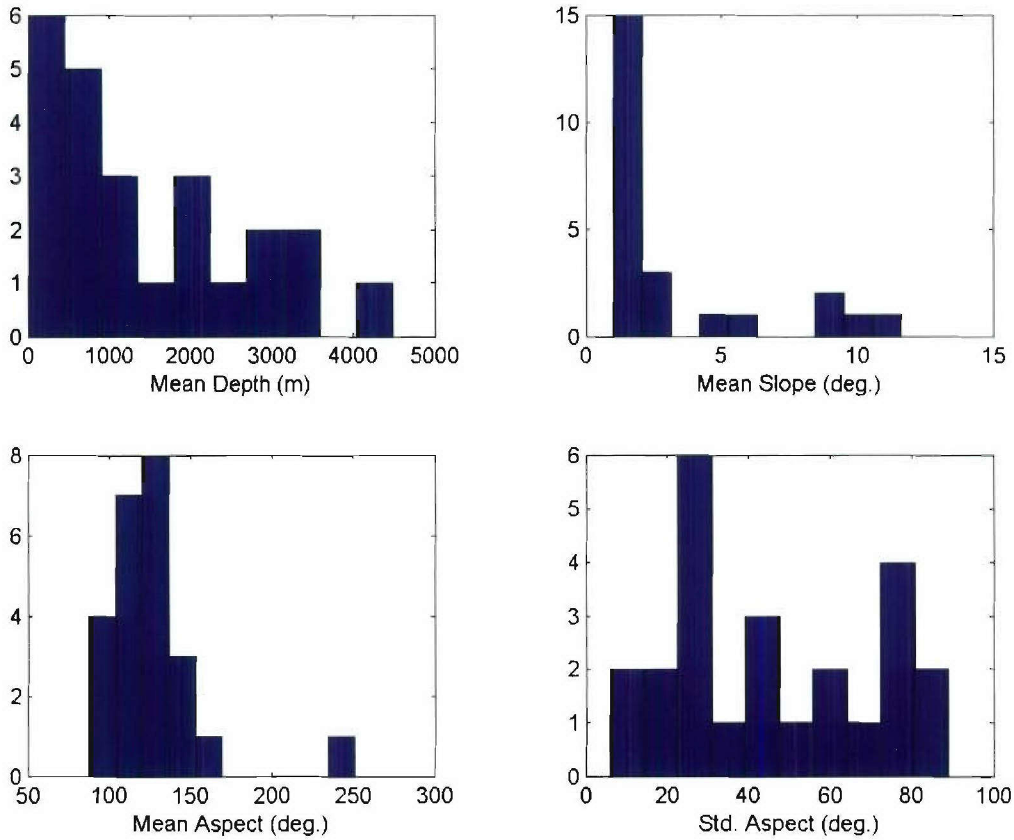


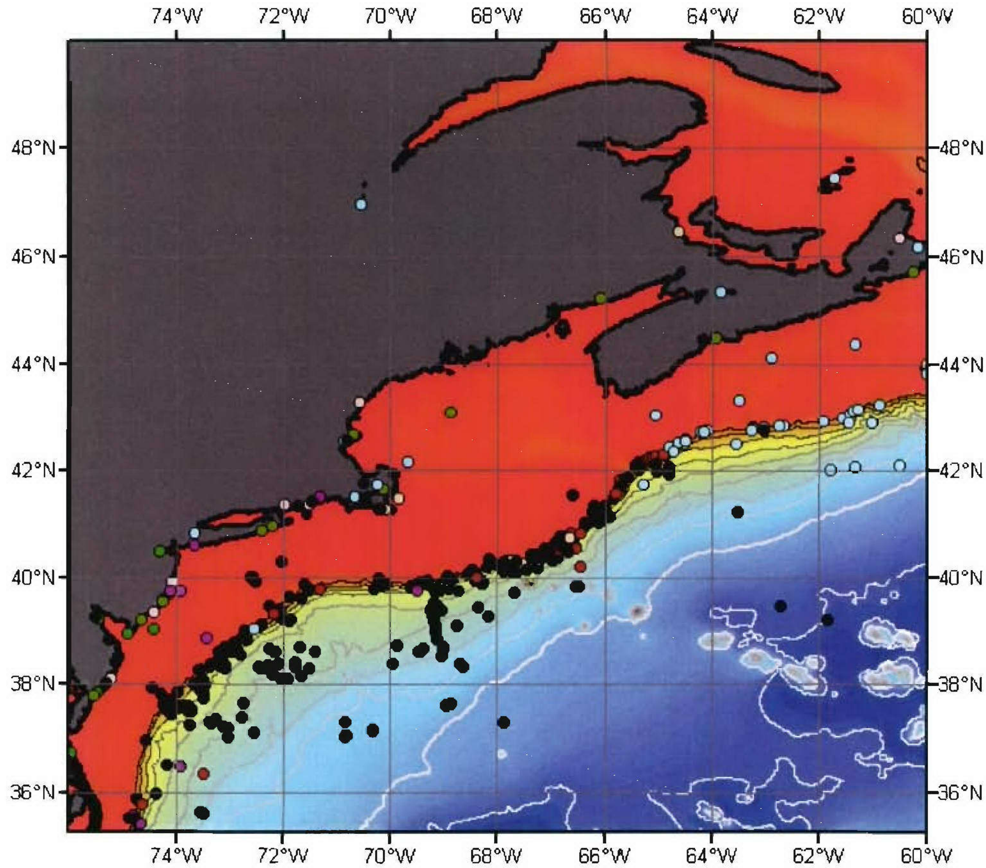
Figure 34. Histograms of Environmental Variables of 9-Minute Cells with Beaked Whale Presence Data in the SEUS

3.4 NORTHEAST UNITED STATES STUDY AREA

Beaked whale data available for the NEUS study area included the following events (number of individuals indicated in parentheses): 8 (20) mass strandings, 75 (75) single strandings, 138 (26) unclassified strandings, 21 (34) unknown, 4 (4) bycatch, 115 (345) visual sightings, 1257 (4528) visual shipboard sightings, and 2 (N/A) opportunistic visual sightings. Species identification for the sighting data was typically limited to genus, but in those cases where a more detailed identification was made, it included *Mesoplodon sp.*, *Mesoplodon densirostris*, *Mesoplodon mirus*, and *Ziphius cavirostris* (figure 35 through 37). Stranding data classification was limited to genus with the exception of *Ziphius sp.* (figure 35).

Static Analysis

The mean depth, slope, aspect, and standard deviation of the aspect for each cell were used to characterize and predict habitat at cell resolutions of 5, 10, and 15 minutes.



NORTH-EAST UNITED STATES
Beaked Whale Habitat Characterization and Prediction Program

Prepared by:
Jessica A. Ward
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Code 74

Legend

Sightings
- ● Ziphiidae
- ○ Ziphiidae, Hyperoodon ampullatus
- ○ Ziphiidae, Mesoplodon bidens
- ● Ziphiidae, Mesoplodon sp.
- ● Ziphiidae, Ziphius cavirostris

Strandings
- ● Ziphiidae
- ○ Ziphiidae, Hyperoodon ampullatus
- ○ Ziphiidae, Mesoplodon bidens
- ● Ziphiidae, Mesoplodon densirostris
- ● Ziphiidae, Mesoplodon europaeus
- ○ Ziphiidae, Mesoplodon mirus
- ● Ziphiidae, Ziphius cavirostris

Bathymetry (m)
High : 0
Low : -5600

Figure 35. NEUS Sightings and Strandings Overlaid on Depth Data

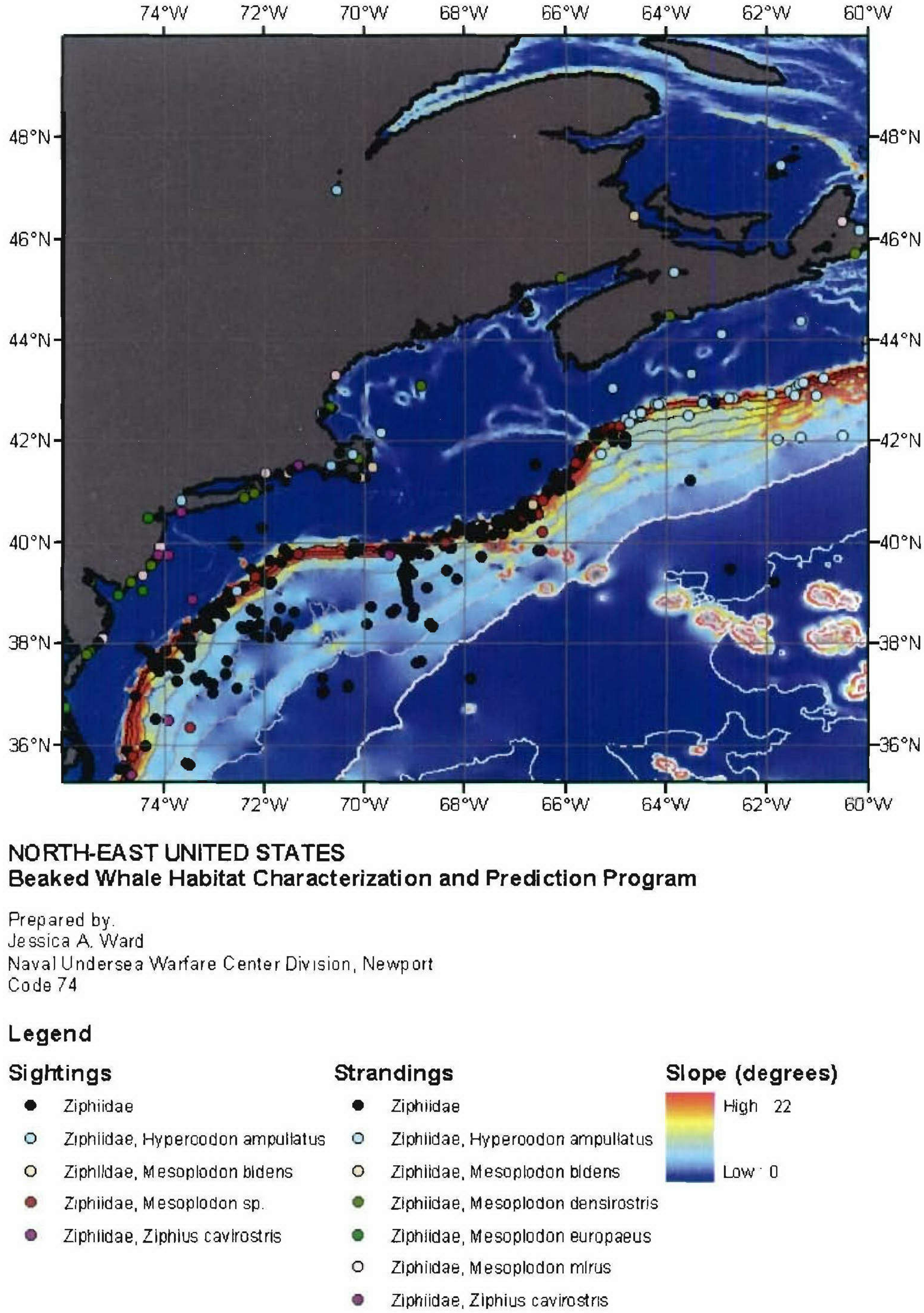


Figure 36. NEUS Sightings and Strandings Overlaid on Slope Data

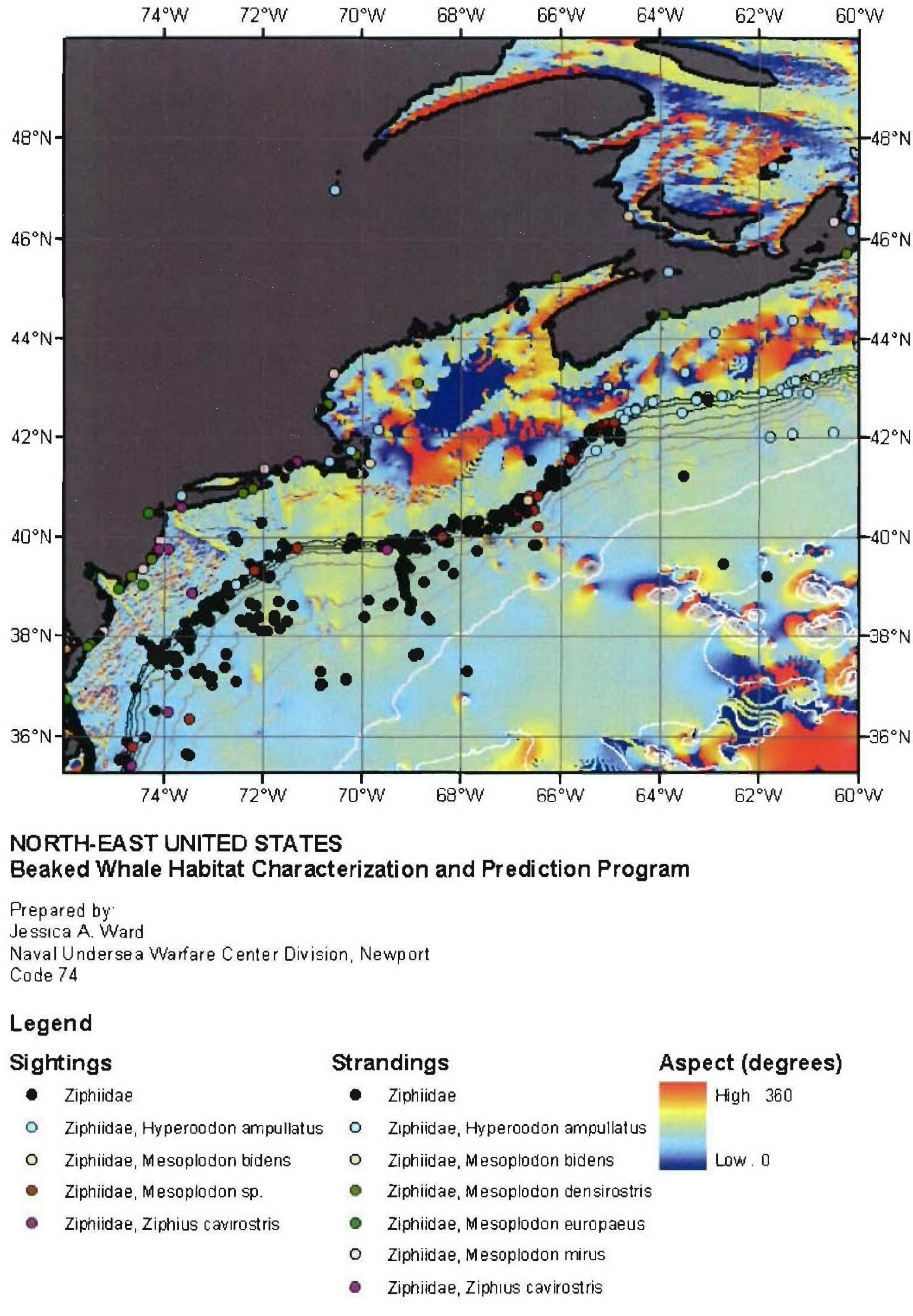


Figure 37. NEUS Sightings and Strandings Overlaid on Aspect Data

Habitat Characterization. Table 13 summarizes the values of 5-minute cells in which beaked whales were present. Even when transformed, no variable passed either the Lilliefors or Jarque-Bera test for goodness of fit to a normal distribution ($P < 0.05$). While the untransformed variables were uncorrelated, the transformed 5-minute variable set for the mean depth and standard deviation of the aspect were correlated ($r > 0.5$). For all resolutions, the mean depth, mean slope, mean aspect, and standard deviation of aspect of cells with beaked whales present differed significantly from those with beaked whales absent (Kolmogorov-Smirnov test, $P < 0.05$).

Table 13. Habitat Characteristics of 5-Minute Cells with Beaked Whales Present in the NEUS (N=84)

Variable	Minimum	Maximum	Mean	Standard Deviation
Mean depth (m)	89.84	5009.29	2036.85	1117.21
Mean slope (°)	0.08	6.85	2.48	2.04
Mean aspect (°)	96.47	216.31	142.36	21.44
Std dev of aspect (°)	0.50	25.97	6.79	5.68

Classification Effectiveness. The optimal model for each cell resolution based on the mean correct CR is presented in table 14. In all cases, models based on the transformed data performed better than untransformed data. The 15-minute resolution LDA model had the highest mean correct CR.

Table 14. NEUS Static Model Classification Effectiveness Results

Cell Size (min)	Box-Cox	Model	Variables	$N_{present}$	% Present Correct	N_{absent}	% Absent Correct	Mean % Correct
5	Yes	GLM	Depth, Slope, Aspect Std. Dev.	84	79.76	1534	60.56	70.16
9	Yes	GLM	Depth, Slope, Aspect, Aspect Std. Dev.	71	77.46	786	61.96	69.71
15	Yes	LDA	Depth, Slope, Aspect, Aspect Std. Dev.	58	79.31	379	67.28	73.30

Habitat Prediction. The optimal classification model identified (i.e., LDA) was applied to the entire NEUS study area to produce a broader geographic estimation of habitat (figure 38). The presence-absence data used to develop the model are overlaid in figure 39. The mean CR for the 15-minute resolution GLM model, 72.65%, was only slightly less than that of the LDA model. The results of the GLM, along with the upper and lower 95% confidence intervals, are presented in figures 40 through 43 for comparison. For both model results, the predicted habitat is primarily concentrated along the continental slope.

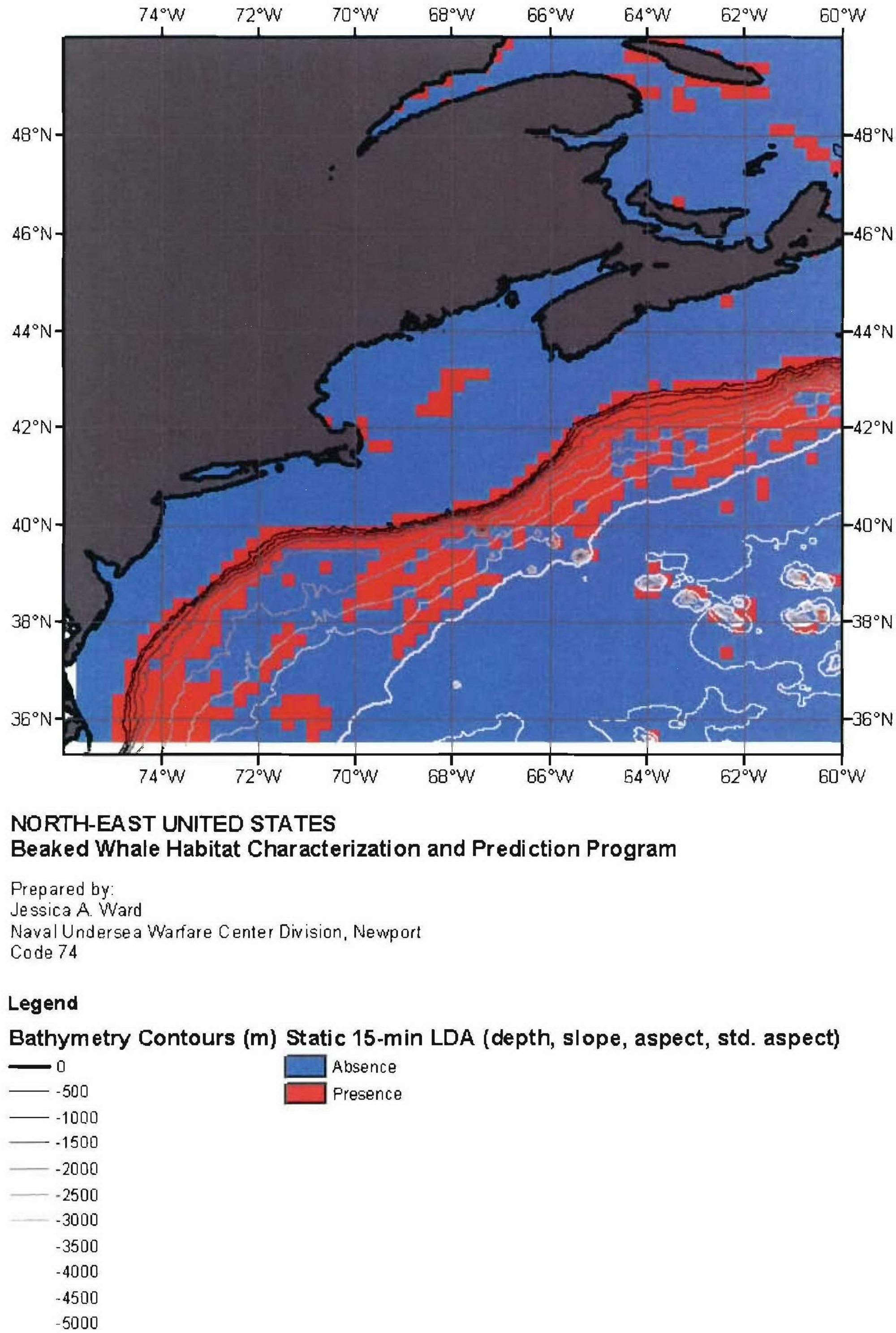


Figure 38. NEUS 15-Minute Resolution LDA Predicted Habitat

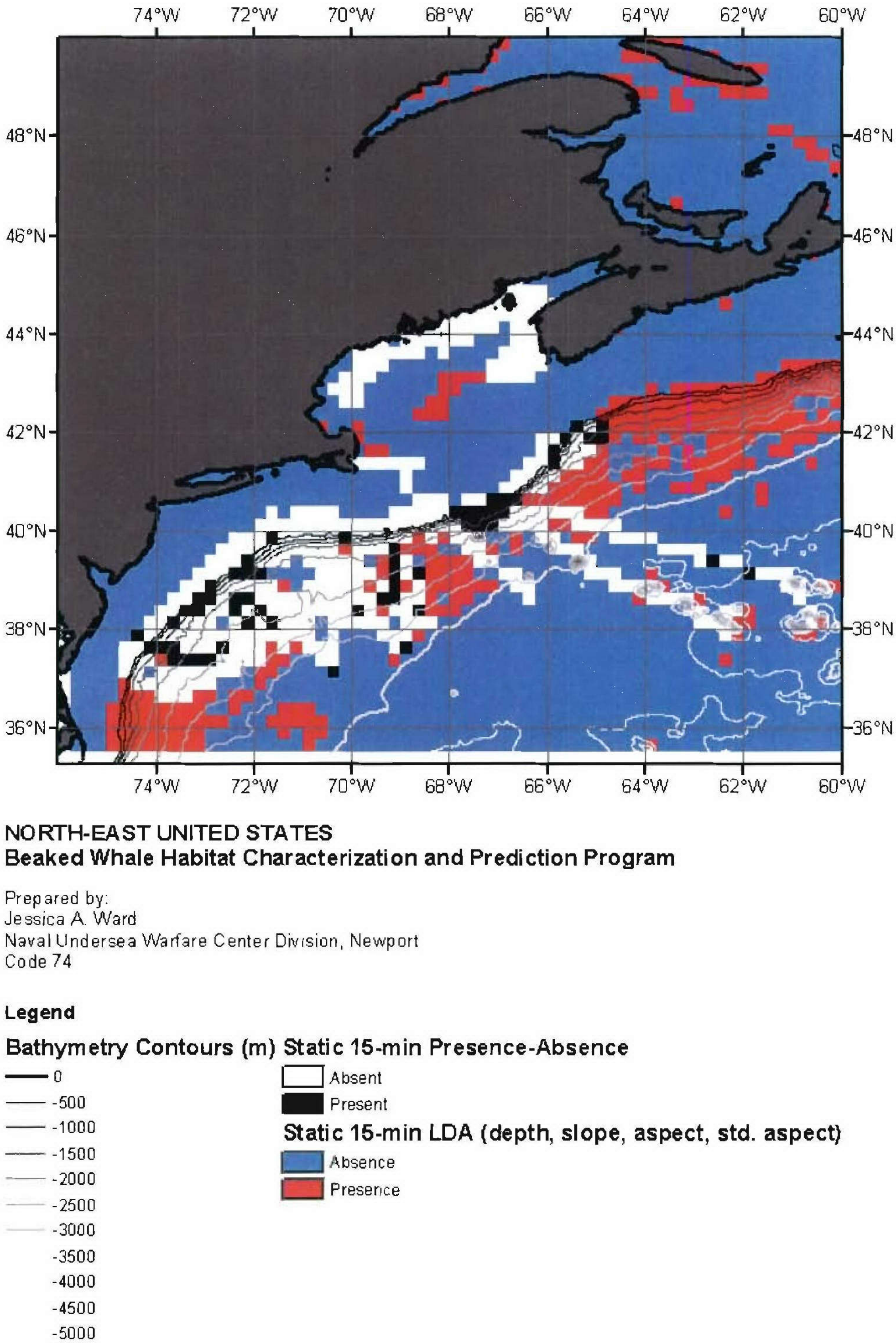
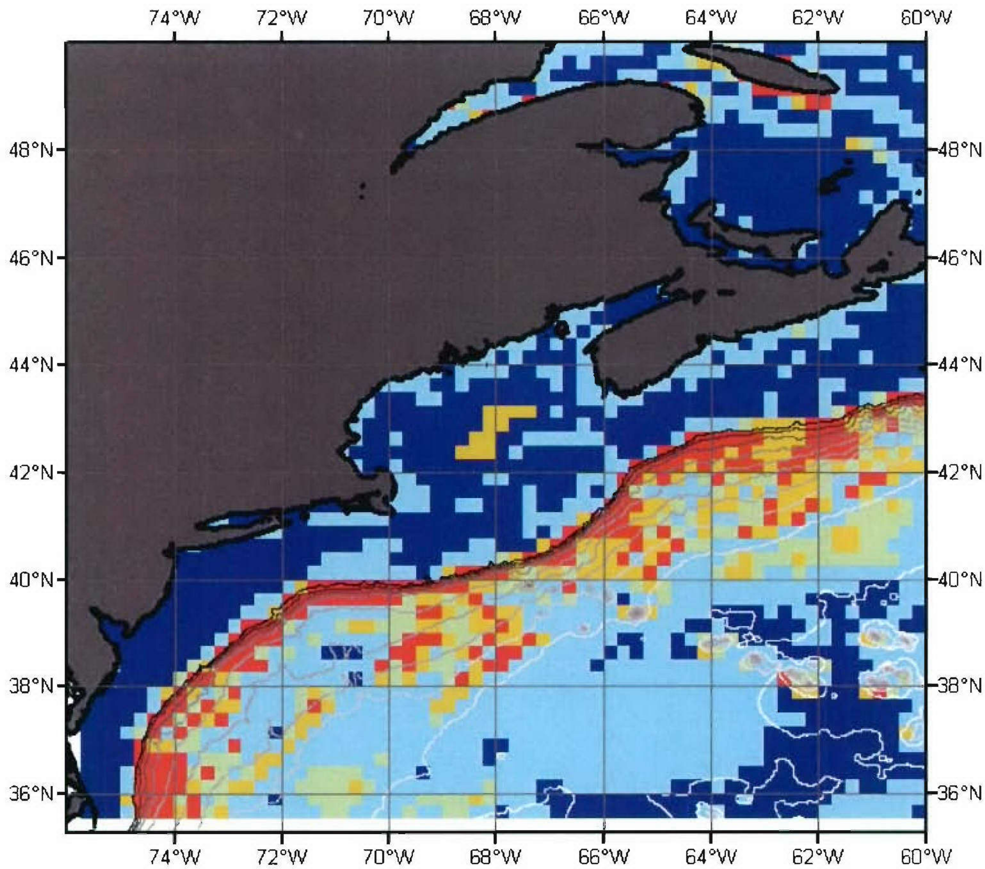


Figure 39. NEUS 15-Minute Resolution LDA Predicted Habitat with Presence-Absence Data Overlaid



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Code 74

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Bathymetry Contours (m)

0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000

Static 15-min GLM (depth,slope,std. aspect)

0.0029 - 0.0245
0.0246 - 0.1327
0.1328 - 0.176
0.1761 - 0.241
0.2411 - 0.6186

Figure 40. NEUS 15-Minute Resolution GLM Predicted Habitat
(Note: GLM values greater than 0.1327 indicate cells classified as present.

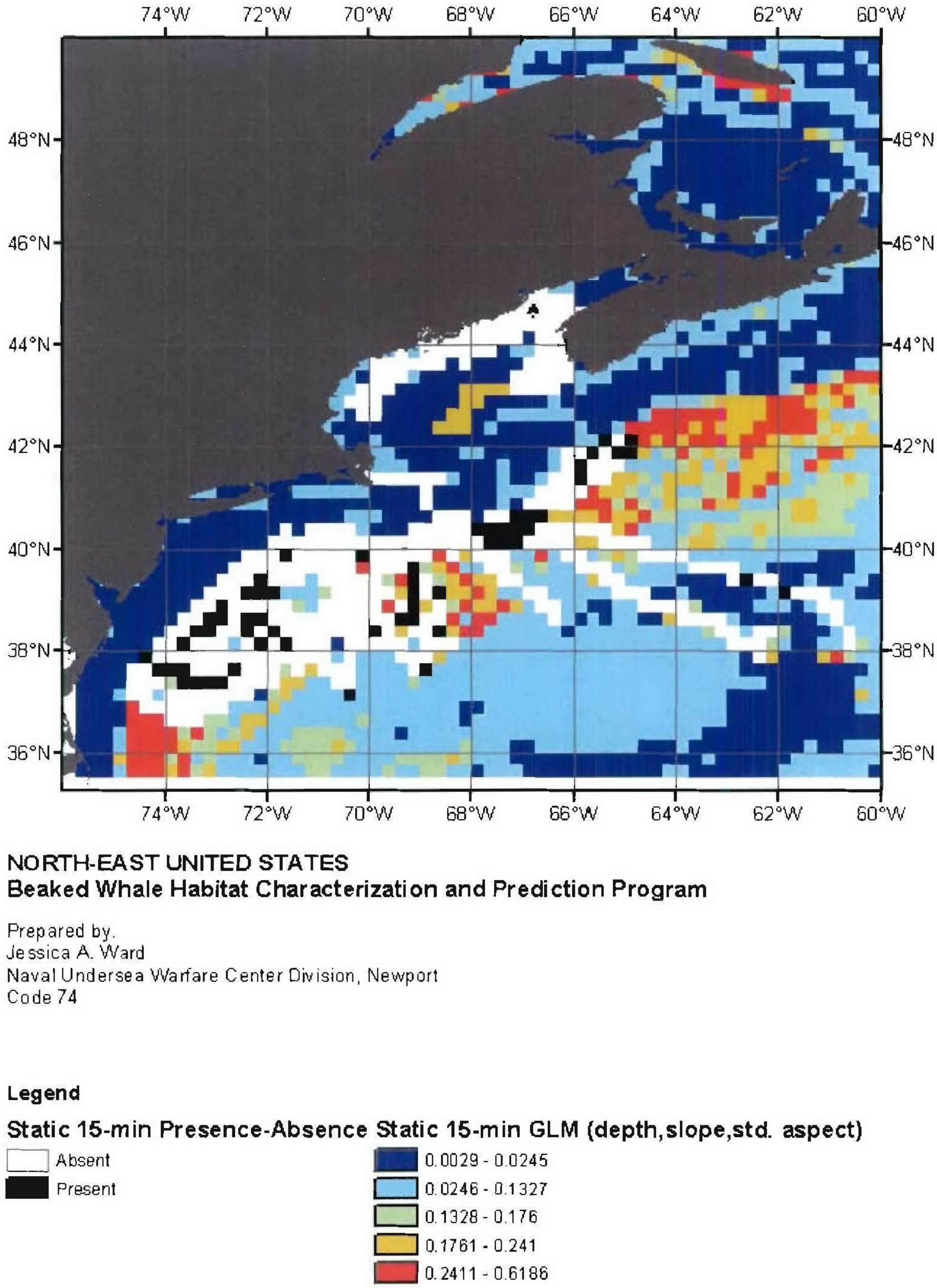


Figure 41. NEUS 15-Minute Resolution GLM Predicted Habitat with Presence-Absence Data Overlaid

(Note: GLM values greater than 0.1327 indicate cells classified as present.)

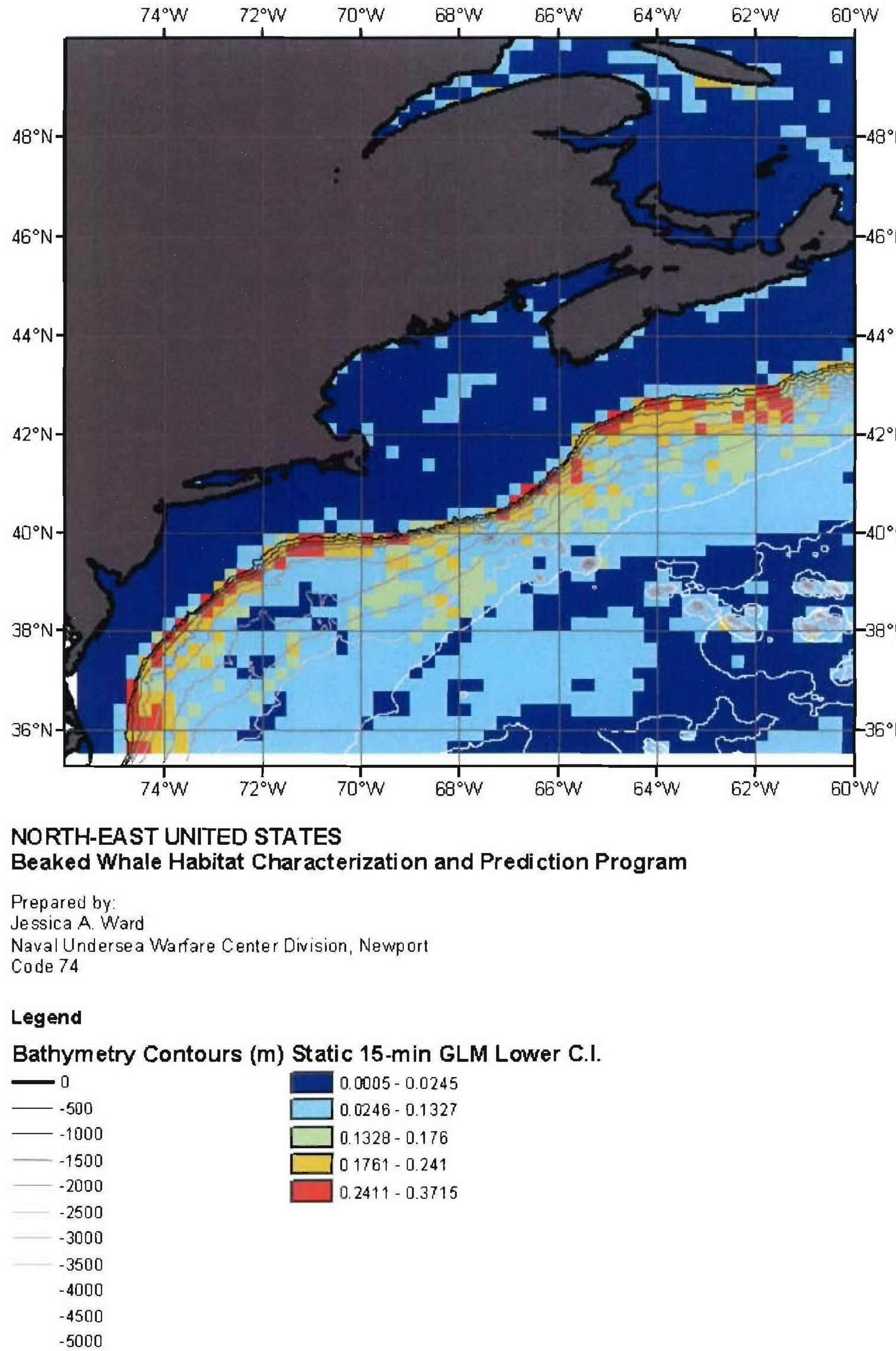


Figure 42. NEUS 15-Minute Resolution GLM Predicted Habitat, Lower Confidence Interval
(Note: GLM values greater than 0.1327 indicate cells classified as present.)

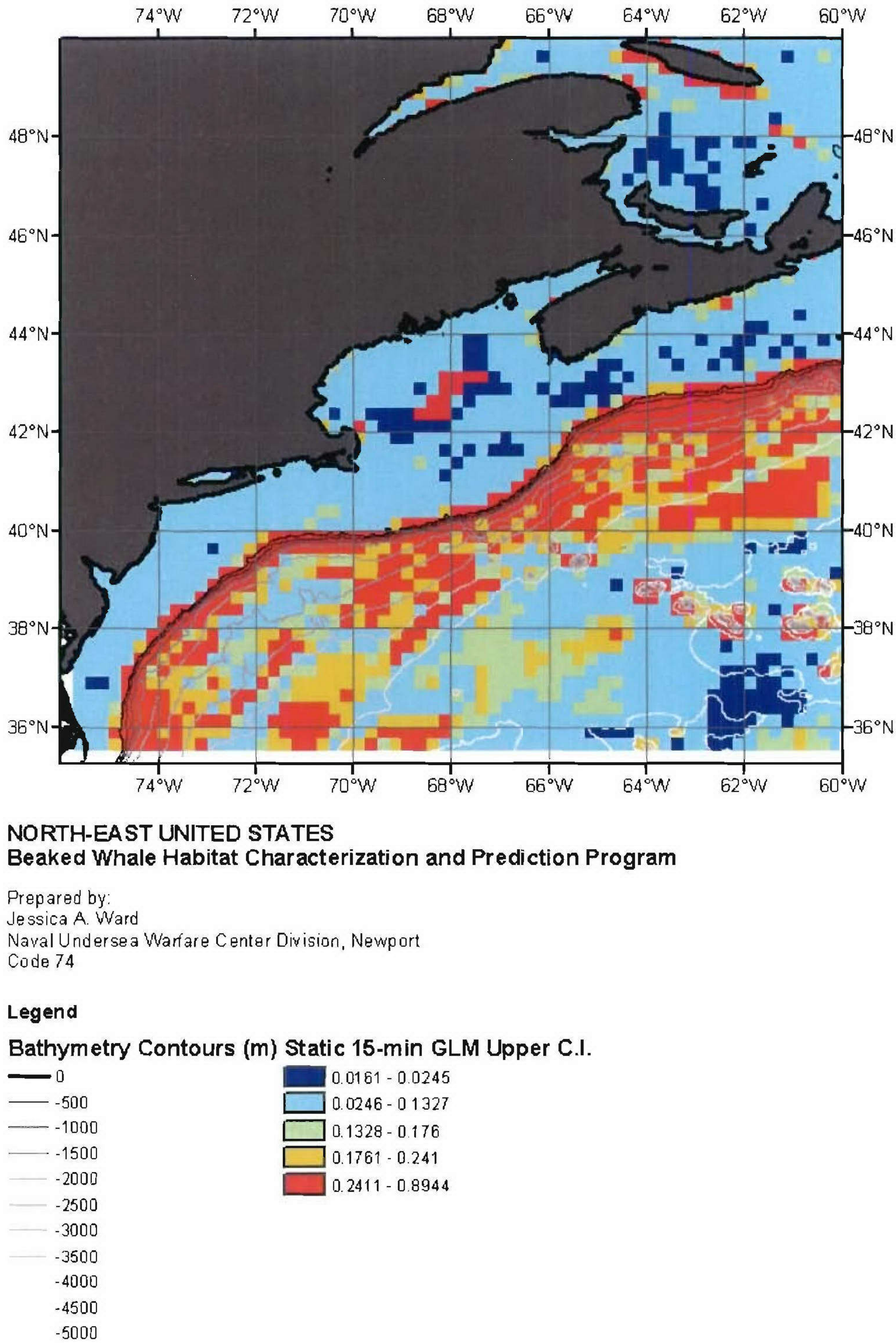


Figure 43. NEUS 15-Minute Resolution GLM Predicted Habitat, Upper Confidence Interval
(Note: GLM values greater than 0.1327 indicate cells classified as present.)

Dynamic Analysis

The following 12 variables were used to characterize the weekly environment for each 15-minute cell: mean depth, maximum difference in depth, slope, standard deviation of slope, mean aspect, standard deviation of aspect, distance to nearest frontal edge, mean frontal frequency, mean SST, standard deviation of SST, mean SSH, and standard deviation of SSH.

Habitat Characterization. Table 15 summarizes the values of 15-minute cells in which beaked whales were present. While transforming the variables did bring them closer to a univariate normal distribution, only the mean depth and mean aspect passed the Jarque-Bera test for goodness-of-fit to a normal distribution ($P < 0.05$). Mean depth and maximum change in depth, mean slope and maximum change in depth, mean slope and slope standard deviation, mean depth and mean SST, and mean depth and mean SSH were correlated for both the transformed and untransformed data sets ($r > 0.50$). The values of cells with beaked whales present differed significantly from those with beaked whales absent for the following variables (Kolmogrov-Smirnov test, $P < 0.05$): mean depth, maximum change in depth, mean aspect, mean SST, standard deviation of SST, and mean SSH. The distribution of values for cells with beaked whales present is shown in figure 44.

Table 15. Habitat Characteristics of 15-Minute Cells from Dynamic Analysis with Beaked Whales Present in the GOM (N = 49)

Variable	Units	Minimum	Maximum	Mean	Standard Deviation
1. Depth (mean)	m	672.76	4956.19	2339.91	1038.46
2. Depth (max D)	m	28.69	2098.98	886.92	699.86
3. Slope (mean)	degrees	0.06	4.61	1.73	1.42
4. Slope (std dev)	degrees	0.01	2.25	0.66	0.74
5. Aspect (mean)	degrees	101.73	212.68	142.64	20.35
6. Aspect (std dev)	degrees	1.03	44.18	12.99	9.52
7. Distance to Front	km	0.23	86.60	18.30	18.02
8. Front Freq. (mean)	% occurrence	0.11	1.00	0.34	0.30
9. SST (mean)	°F	19.00	29.70	24.29	2.60
10. SST (std dev)	°F	0.13	3.17	0.84	0.74
11. SSH (mean)	cm	–64.83	3.39	–52.65	11.02
12. SSH (std dev)	cm	0.52	12.94	2.69	2.83

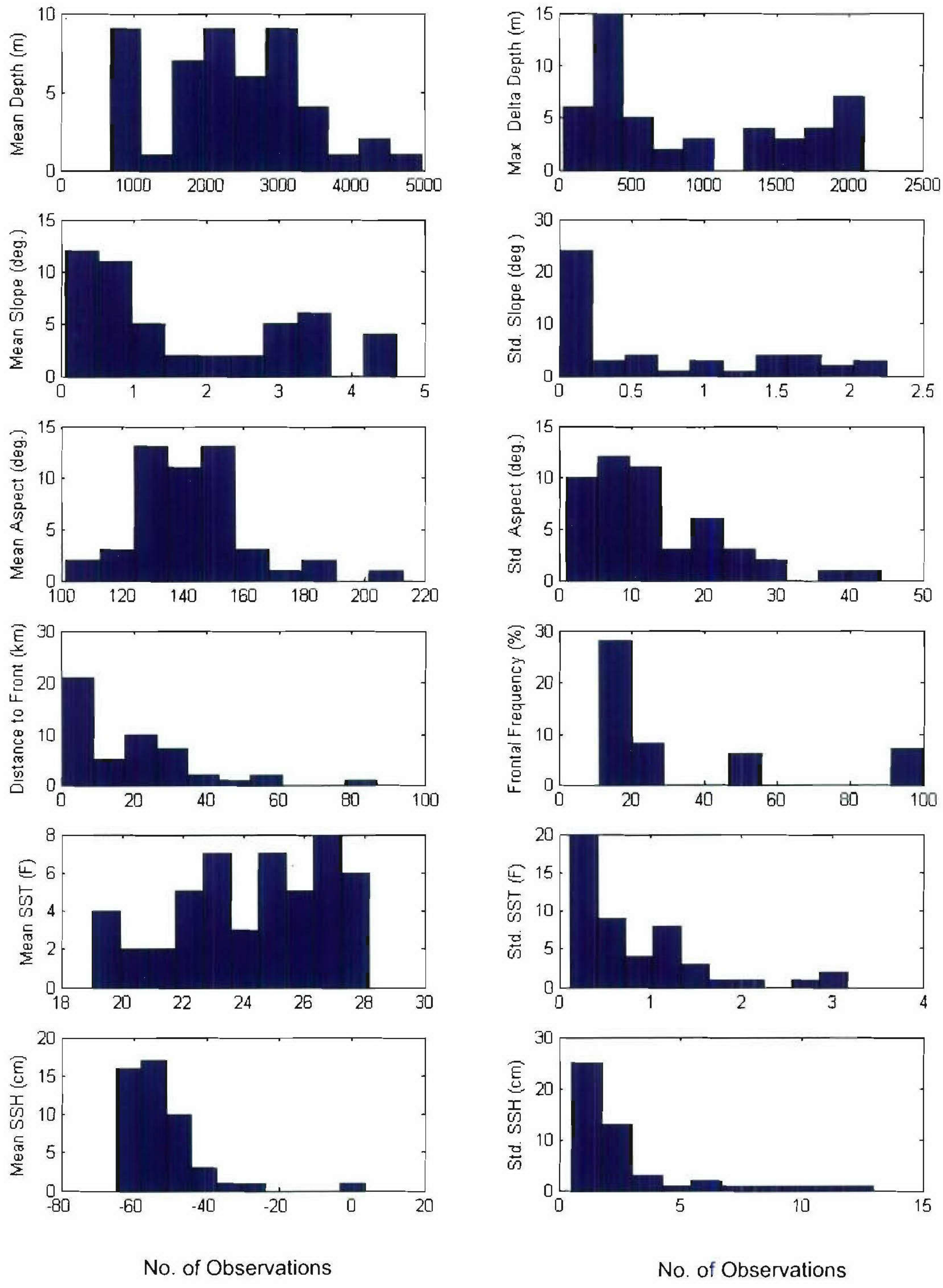


Figure 44. Histograms of Environmental Variables of Cells with Beaked Whales Present in the NEUS

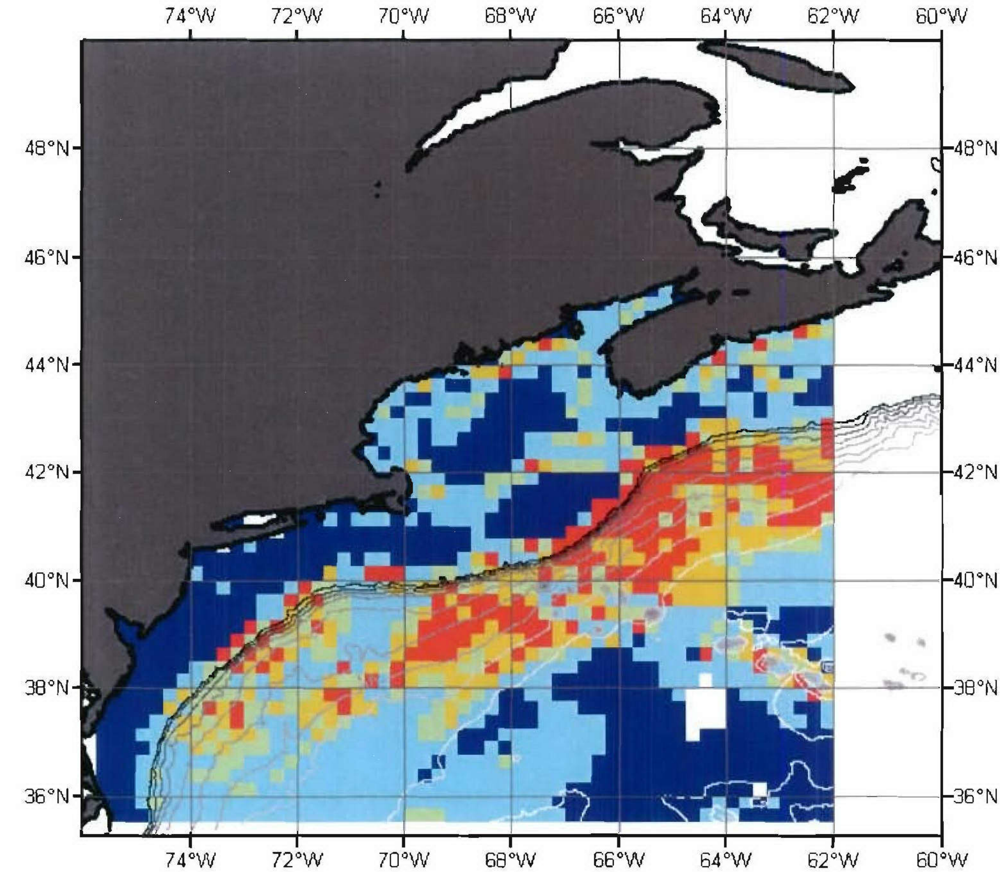
(Note: Label along each histogram applies to x-axis, y-axis equals number of observations.)

Classification Effectiveness. The optimal variable combination for each type of statistical model based on the mean correct CR is presented in table 16. The optimal GLM variable combination reported was determined using all possible variable combinations as opposed to a forward step-wise method. The GLM and LDA models produced similar classification effectiveness results; however, the GLM method required only four environmental variables rather than the six required by the LDA method. Therefore, the GLM using maximum change in depth, mean slope, standard deviation of slope, and mean SST is the suggested dynamic model for the NEUS.

Table 16. NEUS Dynamic Model Classification Effectiveness Results

Model	**Box-Cox Trans.**	**Variables**	$N_{present}$	**% Present Correct**	N_{absent}	**% Absent Correct**	**Mean % Correct**
LDA	Yes	Max. Δ depth, std dev of slope, mean aspect, std dev of aspect, distance to front, mean SST	56	83.93	481	67.15	75.54
GLM	Yes	Max. Δ depth, mean slope, std dev of slope, mean SST	56	85.71	481	64.24	74.98

Habitat Prediction. Habitat predictions and the corresponding oceanographic data are presented for Julian days 204-210, 1998, in figures 45 through 49. The optimal classification model, GLM, was applied to the entire NEUS study area in order to produce a broader geographic estimation of habitat (figure 45). This model includes SST as a means of capturing important time-variant environmental changes in habitat. Results from the LDA model are also included for comparison (figure 47). While both the static and dynamic models indicated a higher likelihood of presence along areas with a steep slope, the areas of increased beaked whale presence extended into deeper water in the dynamic example presented in figure 45.



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Bathymetry Contours (m)
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000

GLM (delta_depth, slope, std. slope, SST) 1998 JD 204-210
0 - 0.0139
0.0140 - 0.1043
0.1044 - 0.1572
0.1573 - 0.2247
0.2248 - 0.6685

Figure 45. NEUS 15-Minute Resolution GLM Dynamic Predicted Habitat for 1998, Julian Days 204-210
(Note: GLM values greater than 0.1043 indicate cells classified as present.)

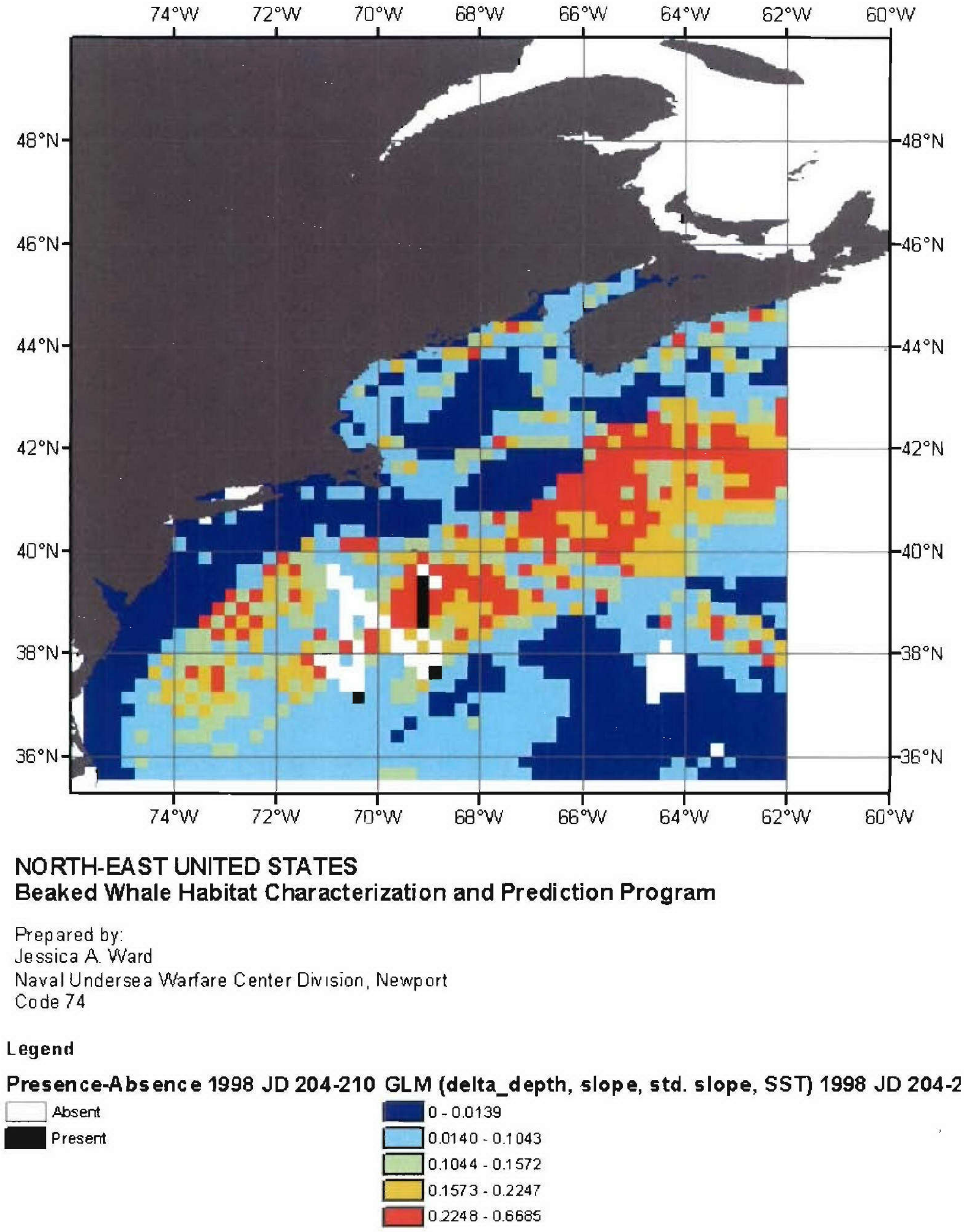

Figure 46. NEUS 15-Minute Resolution GLM Dynamic Predicted Habitat for 1998, Julian Days 204-210 with Presence-Absence Data Overlaid

(Note: GLM values greater than 0.1043 indicate cells classified as present.)

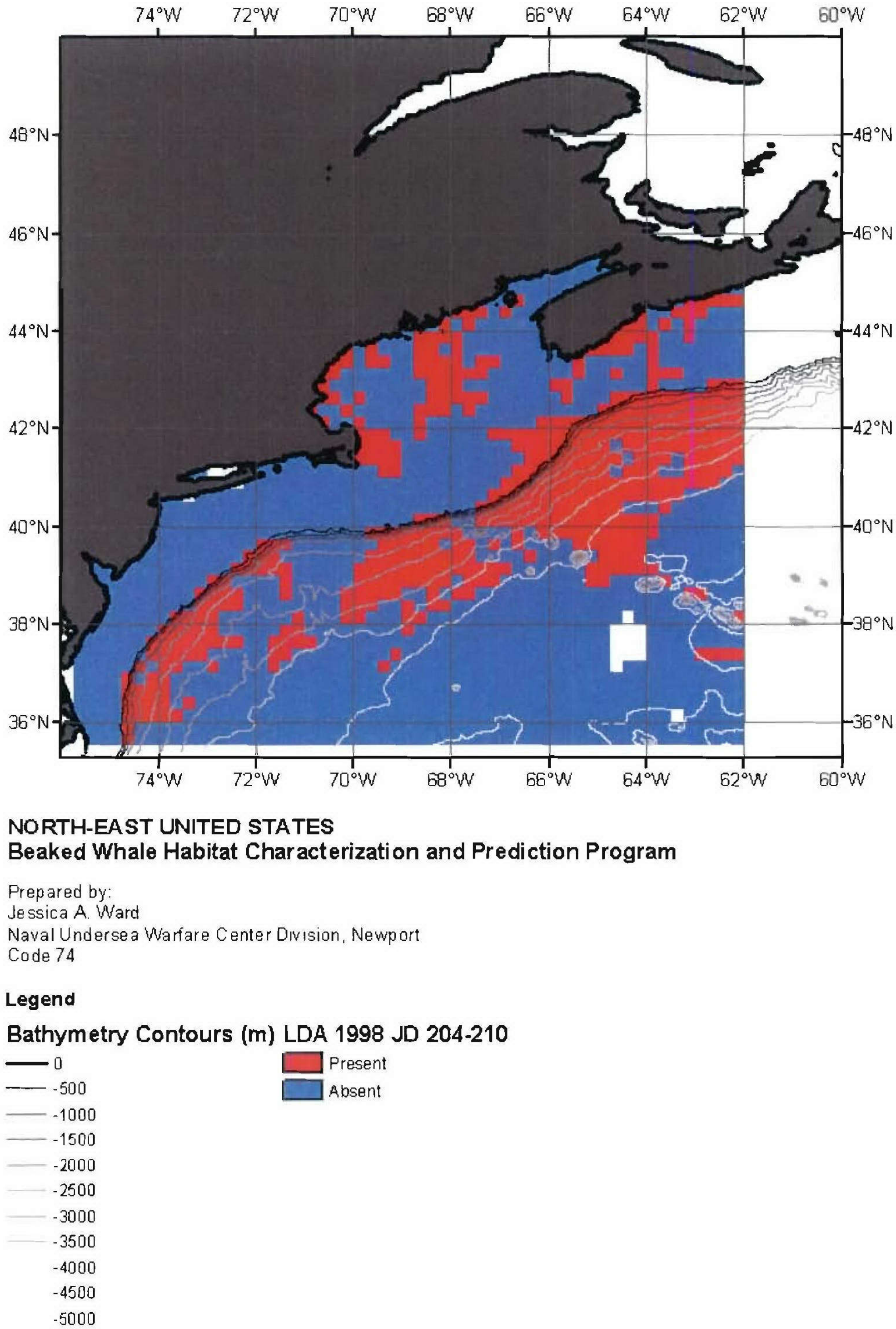

Figure 47. NEUS 15-Minute Resolution LDA Dynamic Predicted Habitat for 1998, Julian Days 204-210

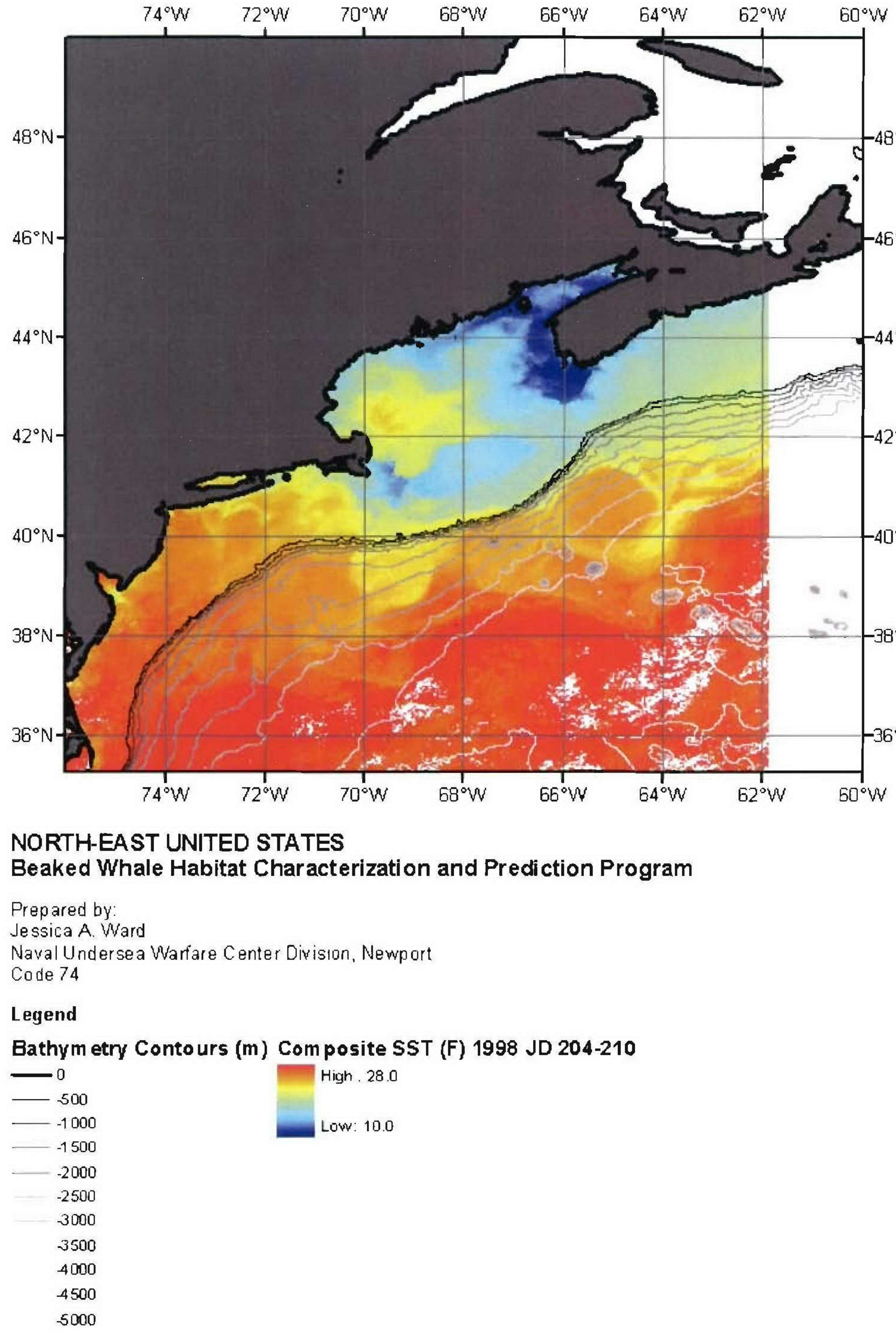

Figure 48. NEUS Composite Sea Surface Temperature for 1998, Julian Days 204-210

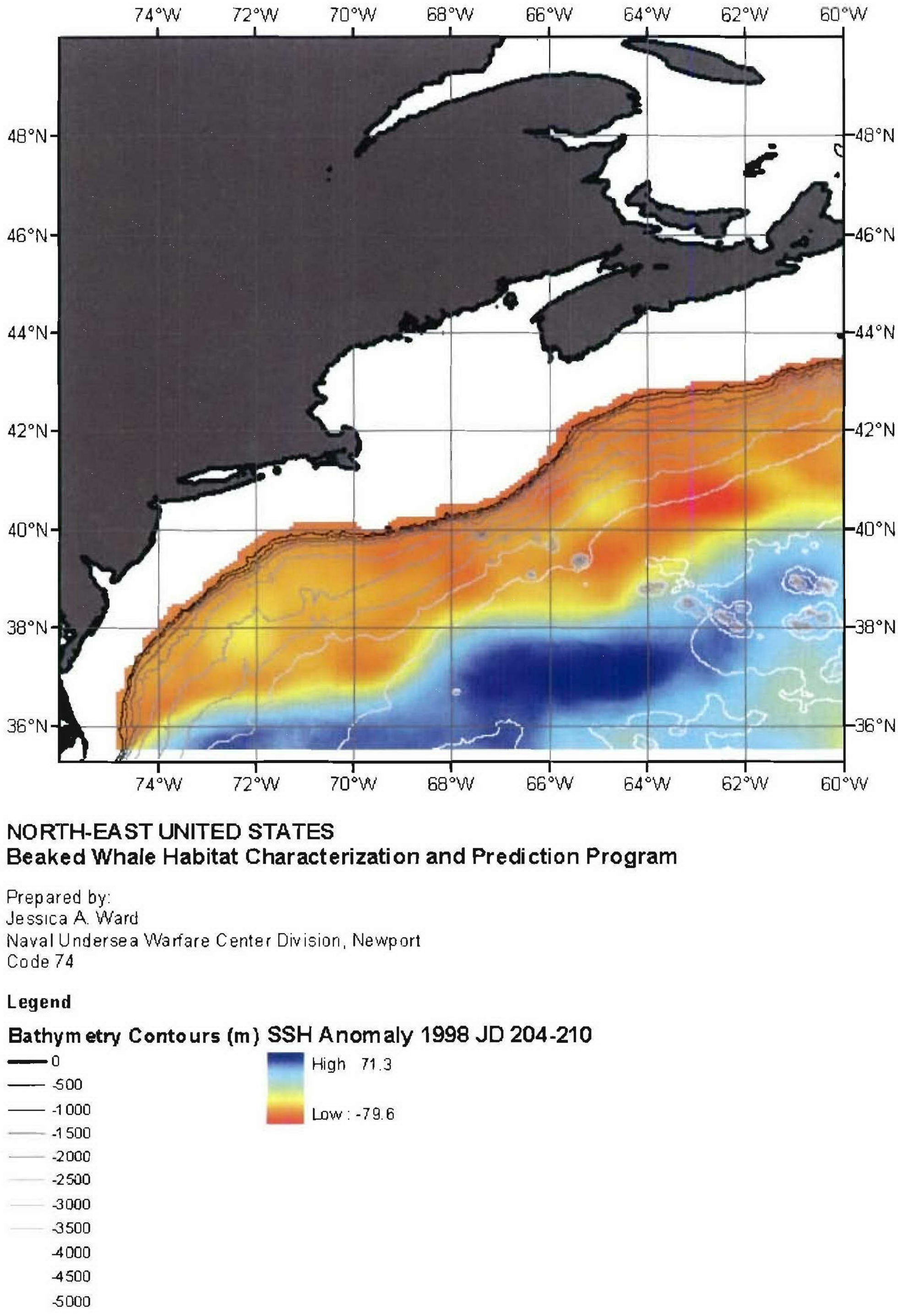

Figure 49. NEUS Composite Sea Surface Height Anomaly for 1998, Julian Days 204-210

4. CONCLUSIONS AND RECOMMENDATIONS

Beaked whale habitat prediction has been demonstrated as a promising and effective statistical technique for defining beaked whale habitat in regions where survey data are minimal or incomplete. The predictive power of the models was assessed using the widely accepted jack-knife method (Guisan and Zimmerman, 2000). Beaked whale habitat optimal classification rate (CR) varied from 73.3% to 81.3% for the static models and 75.54% to 80.26% for the dynamic models of each study area (table 17). The CR for correctly predicting a beaked whale present habitat ranged from 79.3% to 100.0% for the static models and 85.7% to 94.45% for the dynamic models. For all models, the ability to correctly classify habitat in which beaked whales were known to be present exceeded the CR of cells in which beaked whales were identified as absent.

Table 17. Summary of Beaked Whale Habitat Prediction Models with Optimal Classification Effectiveness

Study Area	Static Mean % Correct	Cell Resolution (min)	OSR* (%)	Dynamic Mean % Correct	Cell Resolution (min)	OSR (%)
GOM	77.0	5	1.6	80.3	15	1.4
SEUS	81.3	5	0.3	N/A	15	N/A
NEUS	73.3	15	13.3	75.5	15	11.6

*Observed sighting rate.

This result is not surprising considering the known shortfalls of using marine mammal presence-absence data for habitat prediction modeling. The statistical model assumes the presence-absence data to be an absolute assessment; however, many factors contribute to the observability of beaked whales during surveys, resulting in the model actually predicting the probability of detecting beaked whales in contrast to the actual probability of occurrence (Stauffer, 2002). Beaked whales have long dive times and are difficult to observe in even the best conditions, increasing the likelihood of an animal being present but not being detected during a survey. A location may be surveyed as absent for other environmental reasons—e.g., due to increased ambient noise levels, despite it being a suitable habitat—or the habitat may actually be unsuitable, a "true" value of absence (Hirzel et al., 2002). Additionally, presence data can be biased when beaked whales are sighted in unsuitable habitat (Hamazaki, 2002). Given these caveats and the intended purpose of the predictions for use in environmental compliance planning, overestimation of suitable habitat is preferable to underestimation.

Scale can also affect the precision and accuracy of the predictive model. With a broader scale, the resolution of the features being quantified is course and may omit certain features, which will result in a larger observed sighting rate (OSR), defined as the ratio of presence cells to total survey cells. A smaller scale more precisely quantifies the ocean environment but it also decreases the OSR. Typically, a larger OSR increases the predictive power of a model, but it

may also reduce the accuracy of the prediction because of the imprecise characterization of the oceanographic environment (Hamazaki, 2002). Three scales (cell size) were used with the static model to assess these effects: 5, 10, and 15 minutes (table 18). A very slight decrease in correct CR was observed with an increase in cell size for the Gulf of Mexico (GOM) and a more substantial decrease in the southeast U.S. (SEUS) study area. However, the stability of the SEUS model is likely questionable due to the extremely small OSR (Wiser et al., 1998). Overall, the correct CR did not vary substantially for the GOM and the northeast United States (NEUS).

Table 18. Summary of CR and OSR for Three Spatial Scales

Scale (cell size)	GOM		SEUS		NEUS	
	CR (%)	**OSR (%)**	**CR (%)**	**OSR (%)**	**CR (%)**	**OSR (%)**
5 min	76.95	1.6	81.3	0.2	70.2	5.2
10 min	76.72	3.8	76.1	0.7	69.7	8.3
15 min	76.71	7.7	62.5	1.1	73.3	13.3

While many GIS habitat models are limited to static, time-invariant models, this study also assessed the possibility of whether the model could be improved by adding time-variant oceanographic parameters derived from remotely sensed SST imagery and modeled SSH anomaly. The addition of these time-variant oceanographic parameters slightly improved the CRs for the GOM and NEUS, despite the decrease in OSR due to the addition of many absence cells using this methodology (table 17). From this, it may be concluded that, while the predictive power of the model only increased slightly, the accuracy of the prediction was substantially increased using time-variant oceanographic parameters. For example, while the 15-minute-resolution static model of the GOM generally predicts suitable habitat in all waters with a depth greater than 1000 m (see figure 15), the dynamic model indicates a maximum probability of presence along specific slope regions decreasing toward the Continental Shelf and abyssal plain (see figure 20). Intuitively, the dynamic model appears to be more representative of suitable beaked whale habitat.

The application of these models to environmental planning is also limited by the seasonality and spatial coverage of the presence-absence data upon which they were trained. In the GOM, surveys were conducted year-round, although the sighting conditions likely deteriorated during the winter months (table 19). In the SEUS, surveys were conducted year-round, but the majority of the survey effort was performed over the Continental Shelf and directed toward sighting right whales. In the NEUS, only a partial data set was received (including effort data), and the data were limited to the months of July through September. All of these factors must be taken into consideration when applying the predicted habitat maps for environmental compliance planning purposes.

Table 19. Monthly Distribution of Beaked Whale Sighting Events in Effort Data Used for Dynamic Modeling

Study Area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GOM	0	4	4	12	90	10	15	6	4	0	2	0
SEUS	0	0	1	0	0	1	18	4	0	0	0	0
NEUS	—	—	—	—	—	—	57	32	2	—	—	—

Note: A distribution of 0 indicates effort data exist, but no beaked whales were sighted.

The beaked whale predicted habitat maps produced by this study are an excellent resource for environmental planners trying to develop a better understanding of beaked whale distribution. For long-range planning, the static habitat prediction maps provide a broad assessment of predicted presence with no additional input required. A more detailed real-time or forecast habitat prediction map can be obtained using the dynamic model with real-time or modeled forecast data for inputs. As the viability of this method has been successfully demonstrated, future efforts should include a more comprehensive effort data set, full incorporation of these demonstrated tools into a GIS or other user-friendly environment, and development of a real-time modeling tool for Navy environmental planners working with at-sea testing and training operators using the demonstrated model. The real-time tool would preferably automatically assimilate Web-based real-time remotely sensed data, such as data available from NOAA, and provide a predictive map with minimal user experience required.

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